Spitzer Constraints on Circumstellar Disk Evolution and Terrestrial Planet Formation

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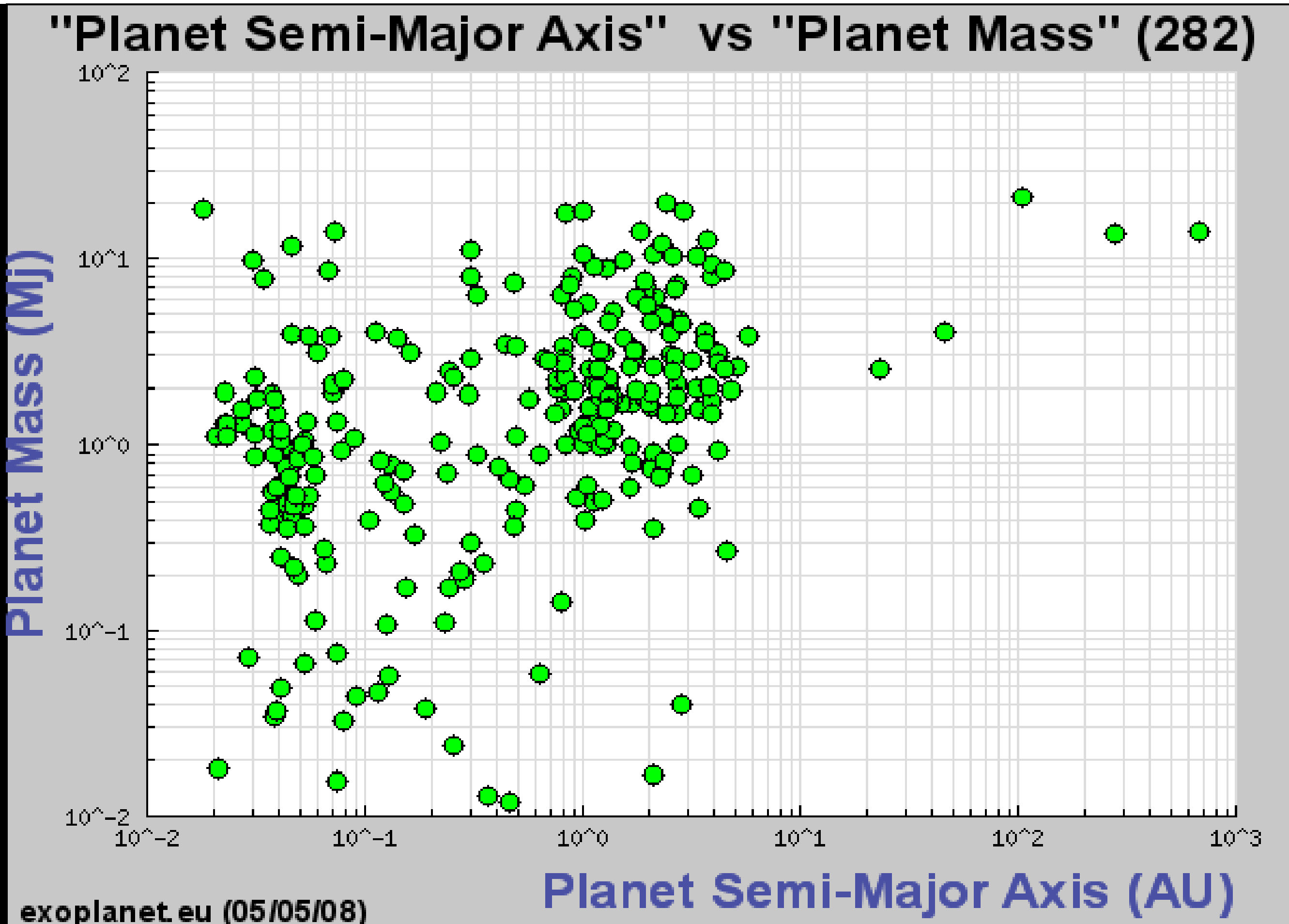
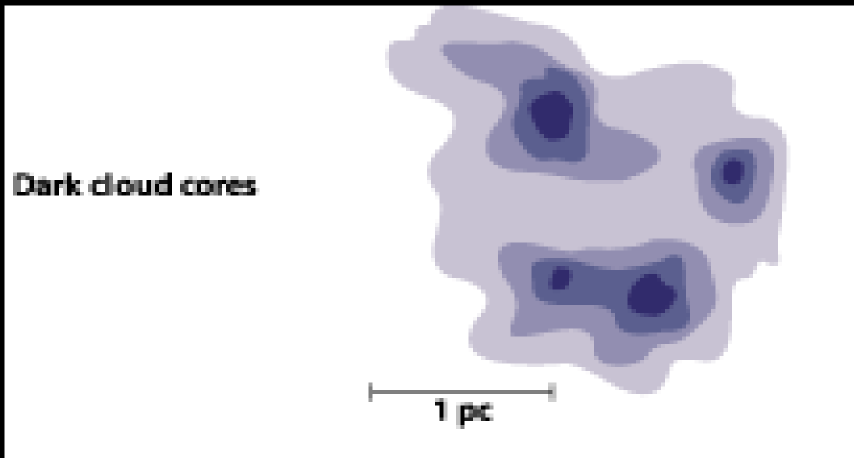


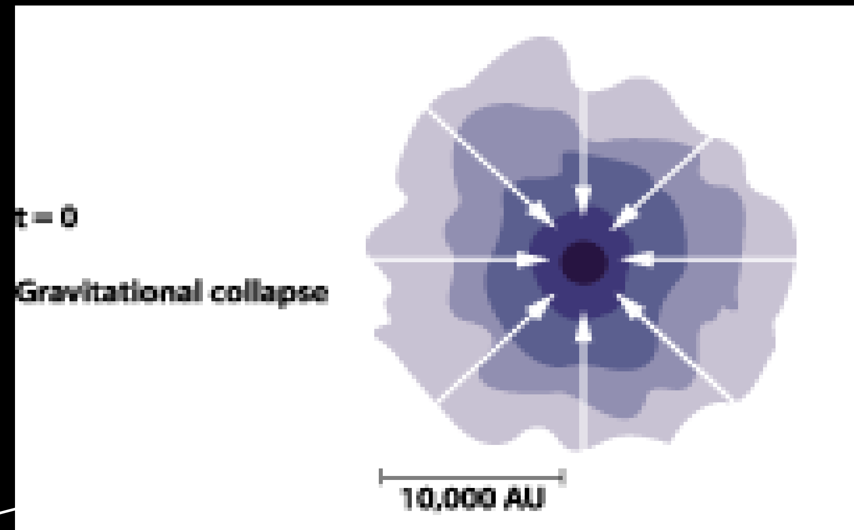
Over 280 known extrasolar planets (many more coming from COROT and Kepler)

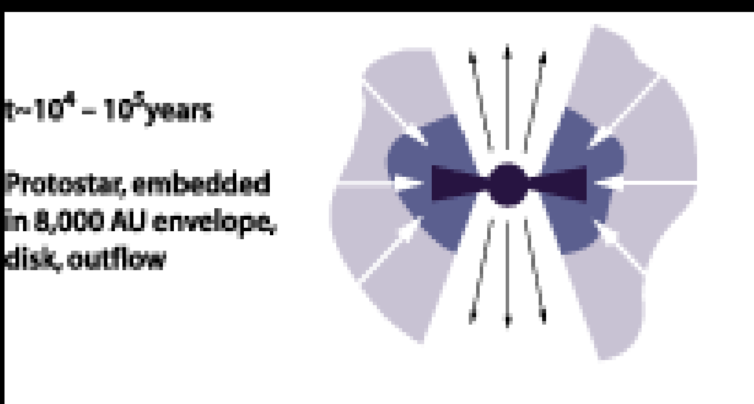
Wide diversity of exoplanet properties

Important point: to understand exoplanets, must understand how they are formed: provides context for (and may explain) observed exoplanet properties

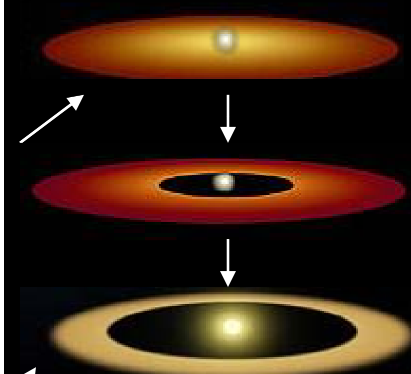
Planets Form in Disks around Young Stars

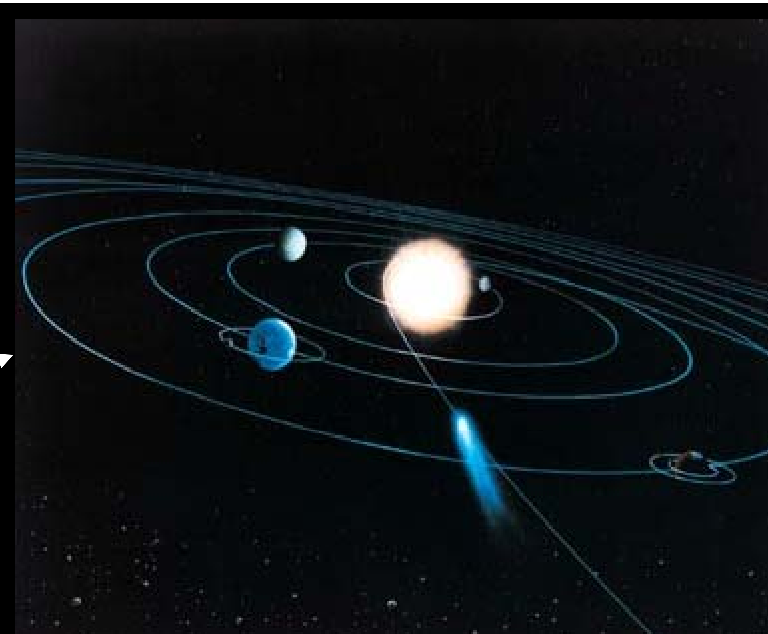






(NASA/Shu, Adams, and Lizano 1987)

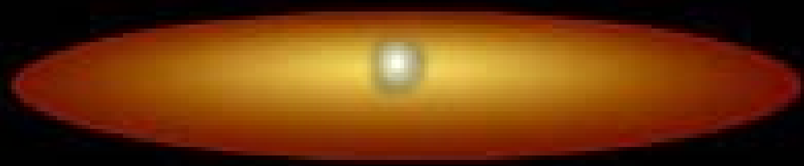


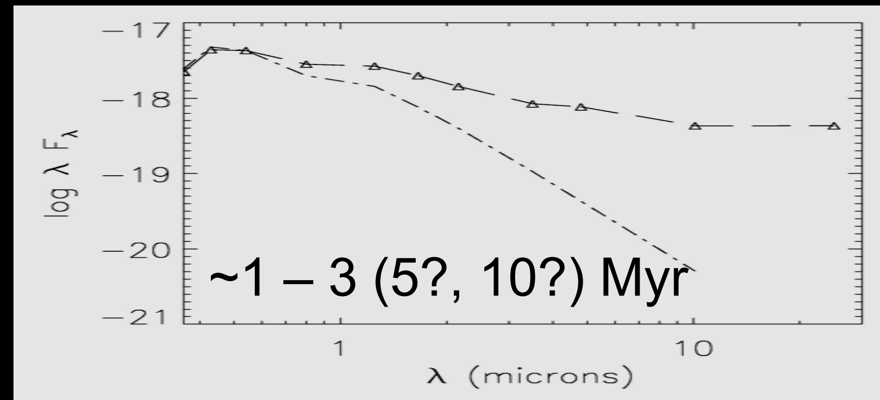


Circumstellar Disk Evolution/Planet Formation

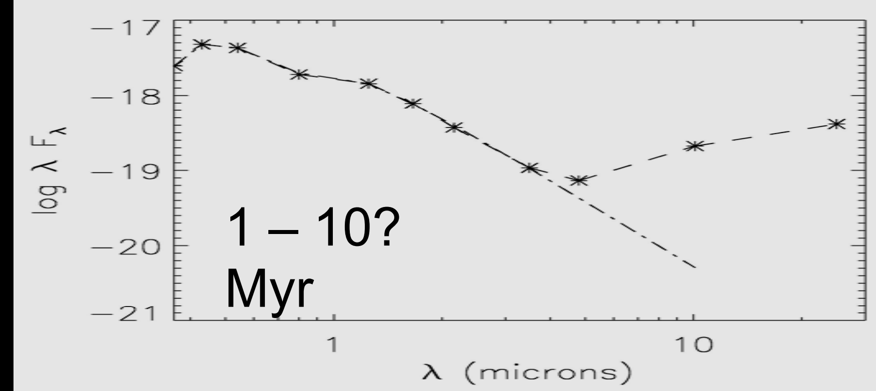
t = 100 Myr- 1 Gyr

A Primer on Circumstellar Disk Evolution

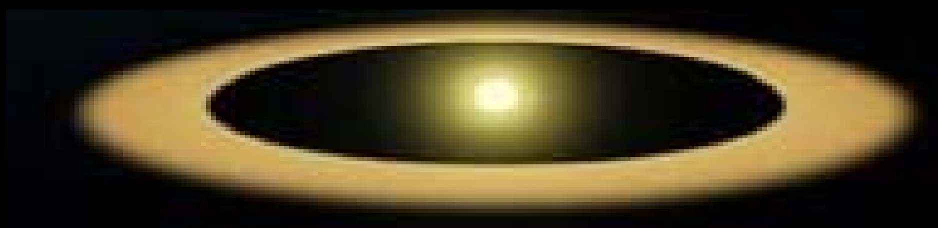


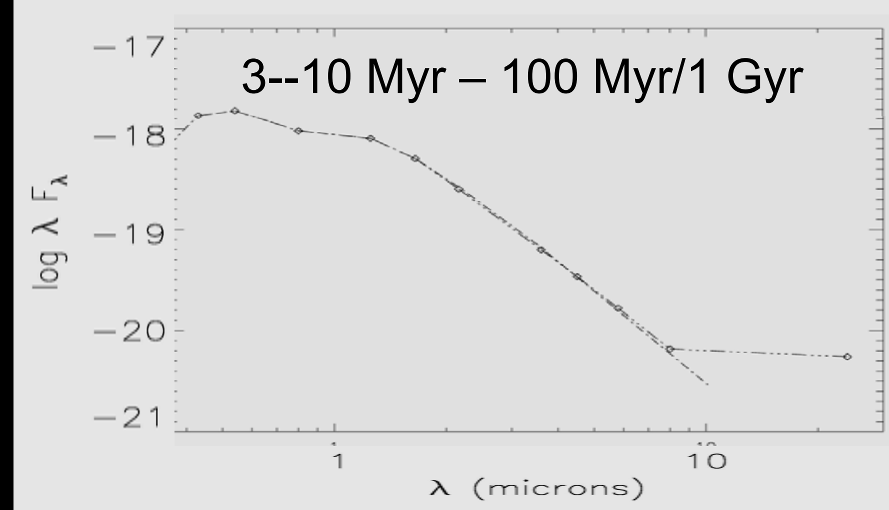


‘**Primordial**’ disk: Accretion; Star+optically-thick disk emission from gas & dust. Excess emission from > 1-2 microns (J—K band)



‘Evolved primordial’(transition) disk: inner holes/gaps, grain growth, gas giant formation?; weak at < 5-10 microns; optically-thick > 10-30 microns

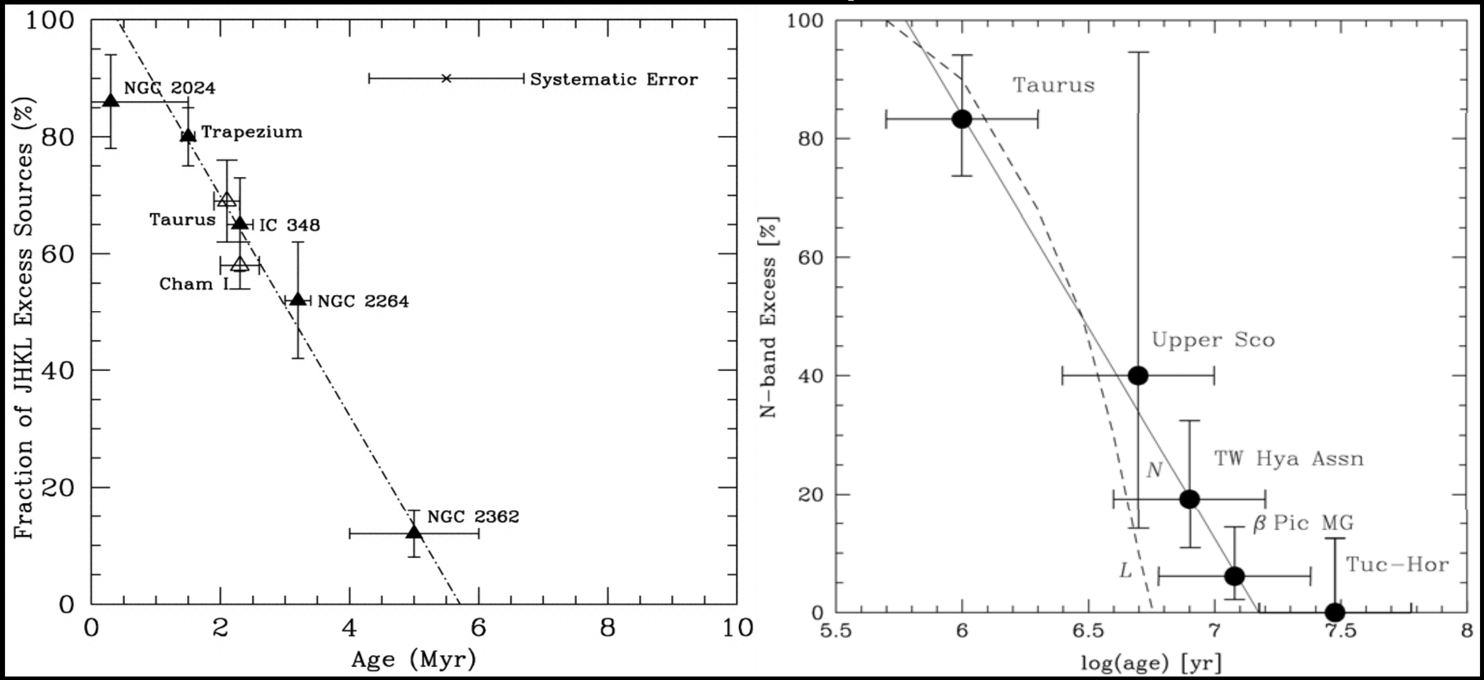




Debris disk: No/little gas; Optically-thin emission > 5-20 microns; dust replenishment → active ***Terrestrial***/ice giant formation; Presence/absence of debris emission → constraints on planet formation

Kenyon & Hartmann 1987, 1995; Backman & Paresce 1993; Kenyon and Bromley 2004

Before Spitzer

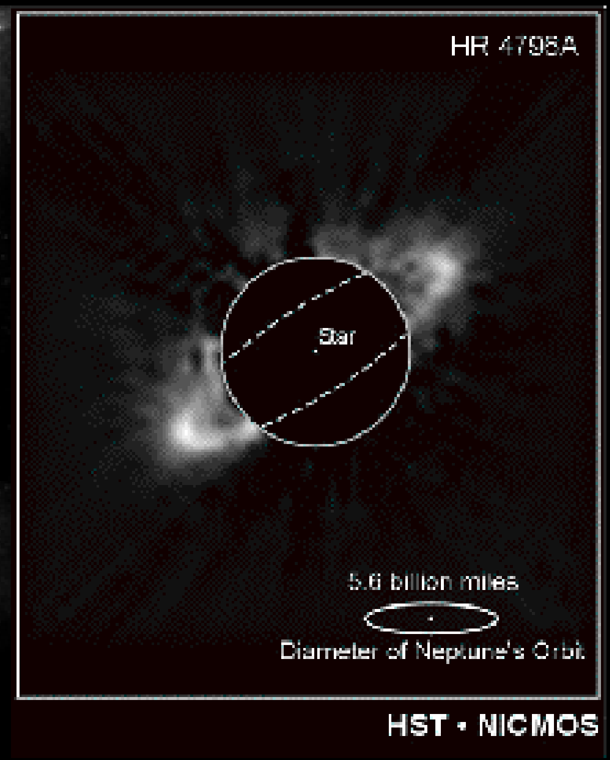


Accretion rate & Frequency of optically thick emission (primordial) declines w/ time (~5-10 Myr; Haisch, Lada & Lada 2001)

Frequency of ~10 micron emission, primordial & warm debris disks (TPF) also declines (Mamajek et al. 2004), is low during epoch of TPF (which is ~10—30 Myr; Kenyon & Bromley 2004)

To constrain gas giant formation, TPF, icy planet formation, need ~3—30 Myr old clusters

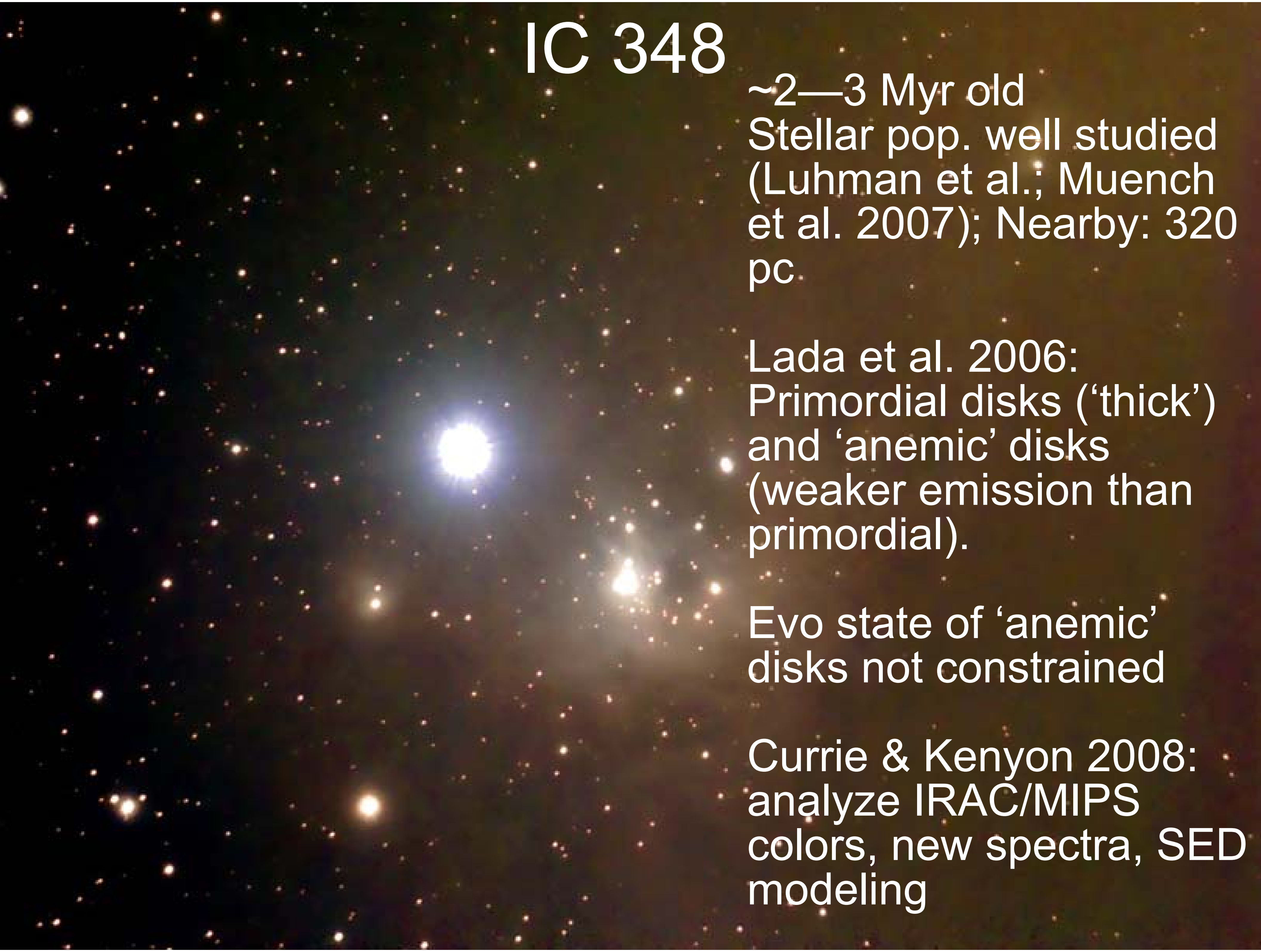
Outstanding Issues in Circumstellar Disk Evolution/Planet Formation



Timescale for gas giant planet formation; primordial-to-debris disk transition

Timescale for terrestrial planet formation/frequency of terrestrial planets

Tracing history of icy planet formation/freq. of icy planets



IC 348

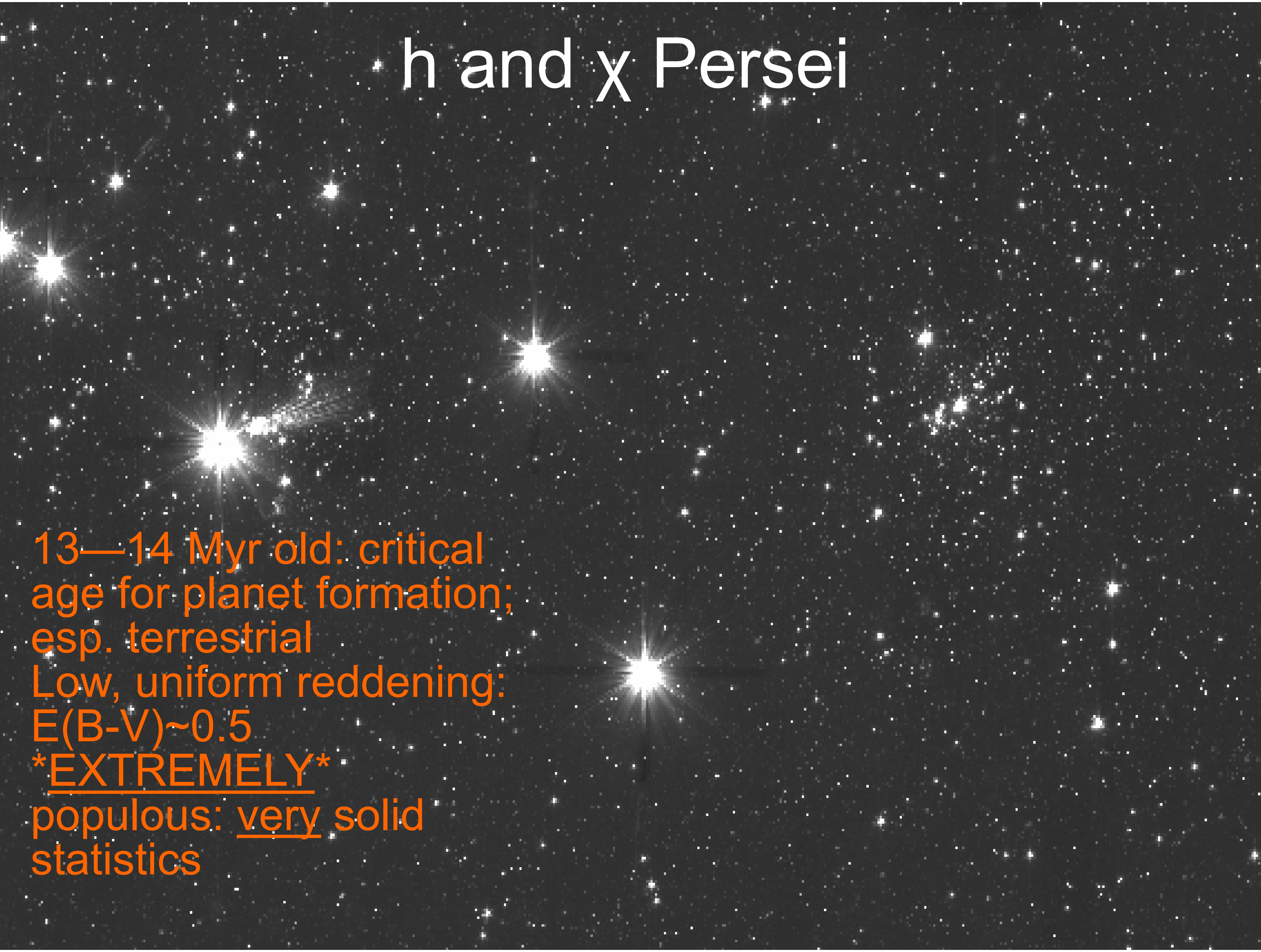
~2—3 Myr old
Stellar pop. well studied (Luhman et al.; Muench et al. 2007); Nearby: 320 pc

Lada et al. 2006: Primordial disks (‘thick’) and ‘anemic’ disks (weaker emission than primordial).

Evo state of ‘anemic’ disks not constrained

Currie & Kenyon 2008: analyze IRAC/MIPS colors, new spectra, SED modeling

h and χ Persei

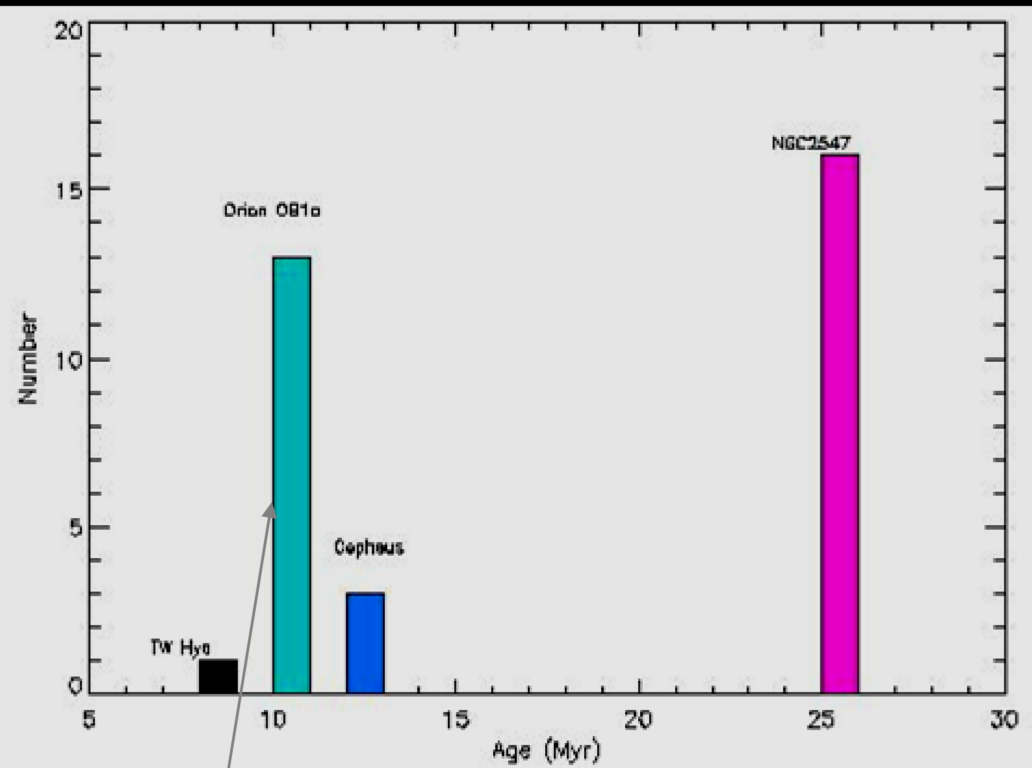


13—14 Myr old: critical age for planet formation; esp. terrestrial

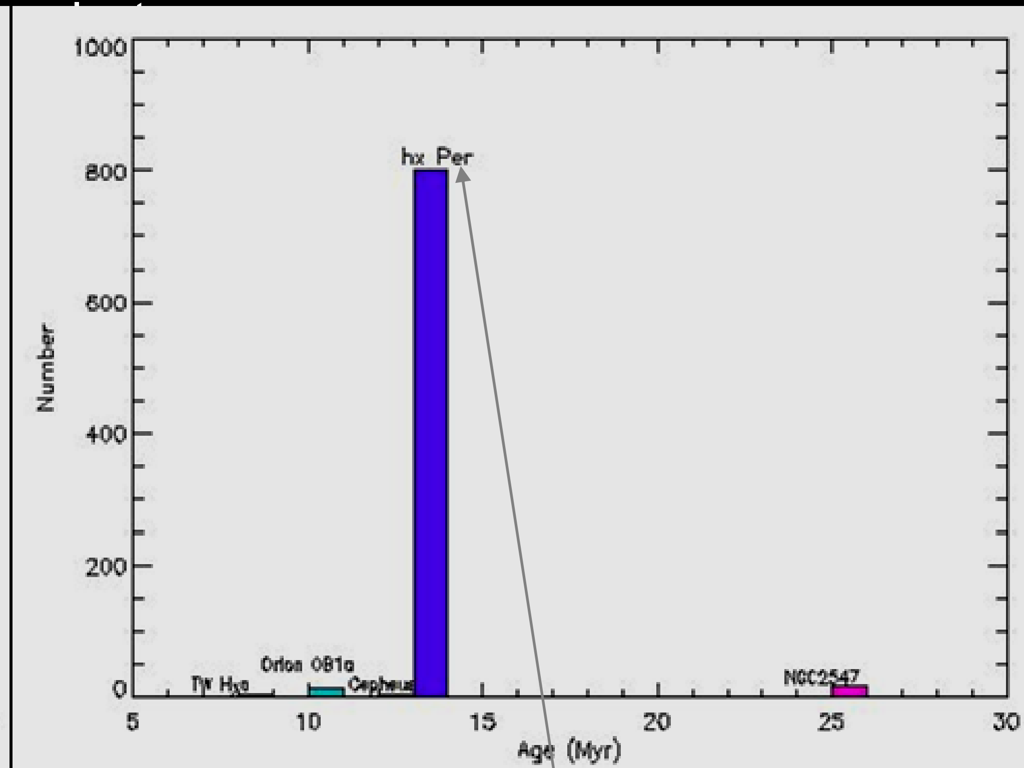
Low, uniform reddening: E(B-V)~0.5

EXTREMELY populous: very solid statistics

h and χ Persei needed to constrain warm dust emission from terrestrial planet formation



Number of A stars for ~10-30 Myr old clusters



Terrestrial planet formation at ~10--30 Myr (e.g. Yin et al. 2002; Kenyon & Bromley 2006)

Warm dust emission (5-10 microns) **is rare** at > 5-10 Myr (Mamajek et al. 2004)

Few high-mass/solar-mass stars in other 10—30 Myr old clusters

Massive clusters needed to study frequency, lifetimes, and evolution of (warm) debris emission from terrestrial planet formation (FEPS too small): **h and χ Persei**

h and χ Persei Observations

Observation	λ	sample size	diagnostic
Opt. Phot.	0.5-0.8	42,000	stellar phot.
Hectospec (spectroscopy)	0.3-0.8	11,500	spec. type, gas accretion
2MASS (photometry)	1-2.2	11,000	star/hot dust (~1000 K)
IRAC (photometry)	4.5-8	5,000-7,000	warm dust (~250-500 K)

IRAC survey probing warm dust from terrestrial planet formation is <u>> 20x larger</u> than all other surveys (e.g. FEPS

NGC 2232

~25 Myr old
Negligible reddening (E(B-V) ~0.05)
Nearby: 320-360 pc

Almost completely ignored by star formation community for past 30 years!!!

IRAC/MIPS Obs. Reduction & Photometry from T. Currie & P. Plavchan

Match with ROSAT archive, proper motion, spectra

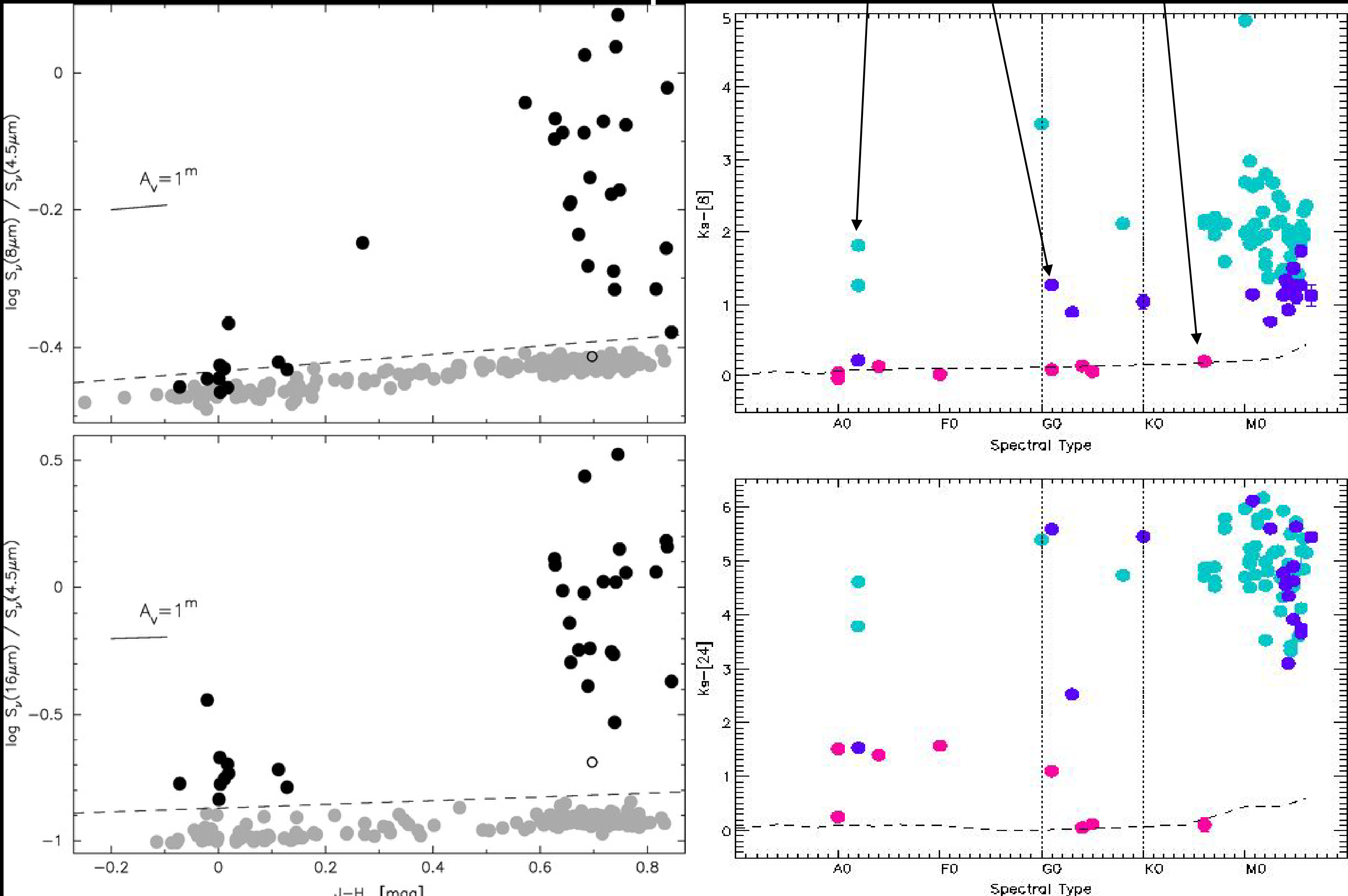
~240 candidate/confirmed

Currie et al. 2008b

Constraining Planet Formation from Spitzer

Goal	Sample	References
Primordial-to-debris disk transition; Timescale for gas giant planet formation (3-15 Myr)	IC 348; Upper Scorpius; h and χ Persei (IRAC/MIPS/spec)	Lada et al. 2006; c2d; Carpenter et al. 2006; Currie & Kenyon 2008; Currie et al. 2007c, 2008c
Timescale for terrestrial planet formation freq. of terrestrial planets (10-30 Myr)	h and χ Persei (IRAC + some MIPS)	Currie et al. 2007a,b; Currie et al. 2008a,c
Tracing history of icy planet formation/freq. of icy planets (10-100 Myr)	h and χ Persei; NGC 2232 (MIPS)	Currie et al. 2008a,b See also FEPS; Trilling et al. 2008; Rieke et al. 2005

Mid-IR colors of 3—5 Myr old stars are stellar mass dependent



Upper Sco (5 Myr)

IC 348 (2-3 Myr)

Carpenter et al. 2006; Currie & Kenyon 2008

Disk Modeling

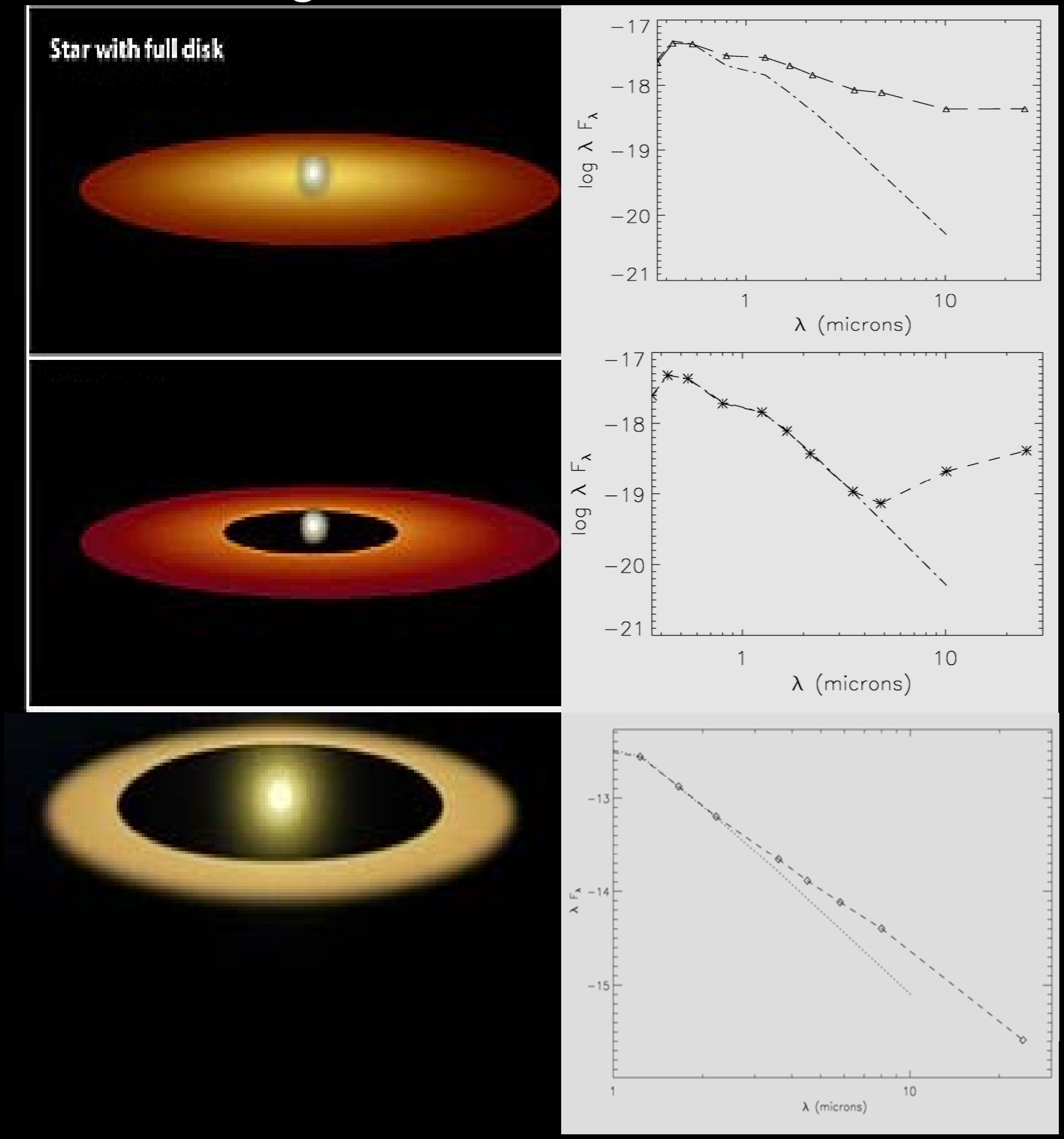
SEDs of early to late-type ‘thick’, ‘anemic’, and ‘diskless’ sources

Primordial disk model (Kenyon & Hartmann 1987)

Evolved primordial disk model

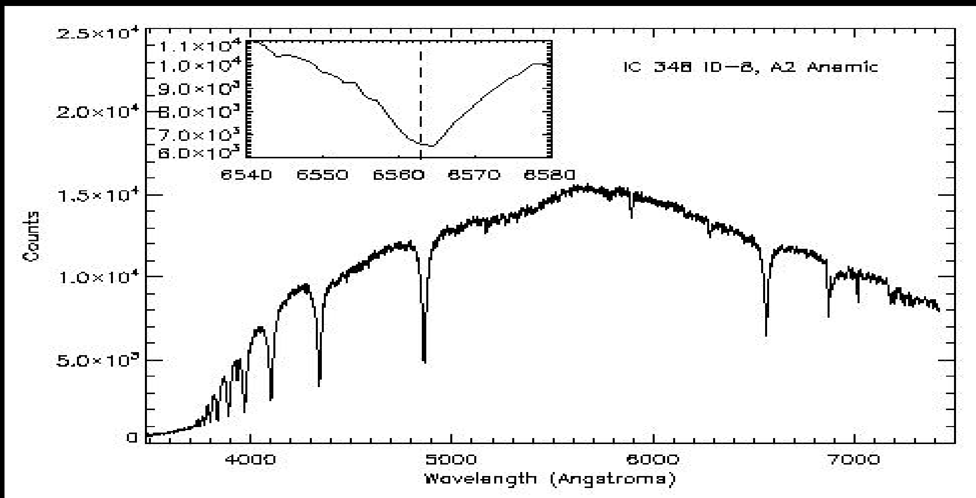
Terrestrial zone debris disk model (2.0 Msun and 3.0 Msun models from Kenyon & Bromley 2004)

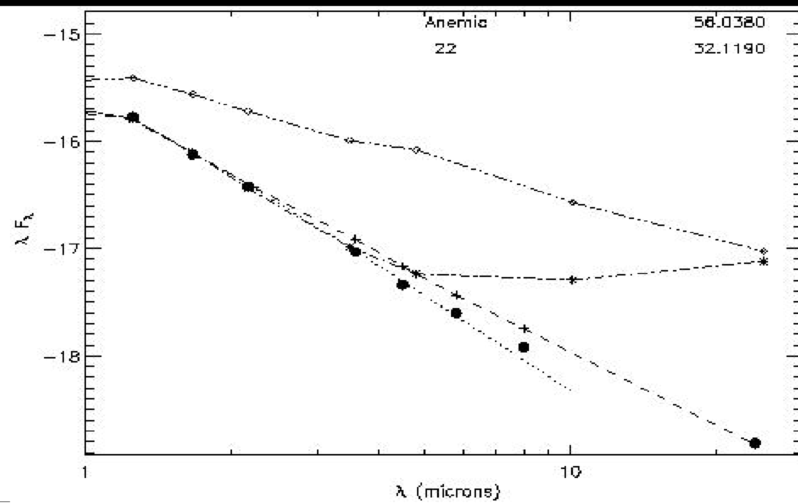
New optical spectroscopic observations: very high signal-to-noise, look for accretion signatures

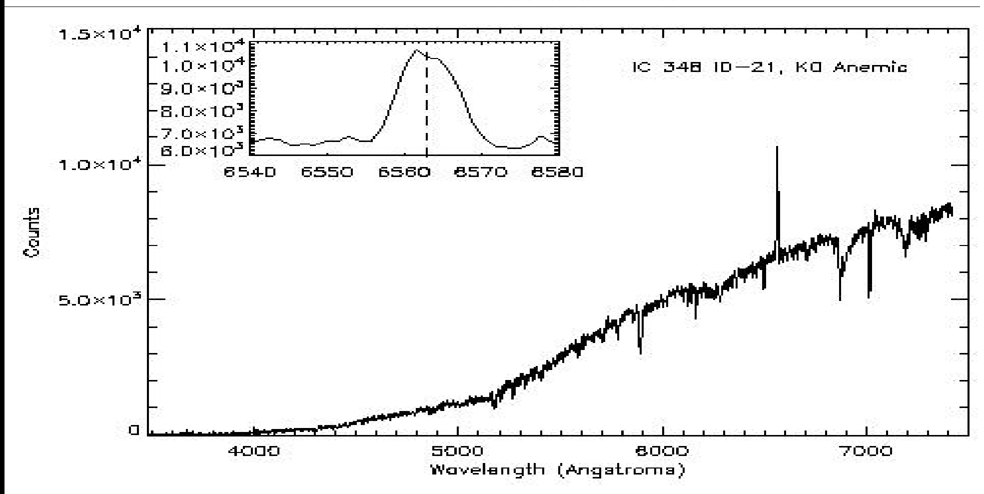


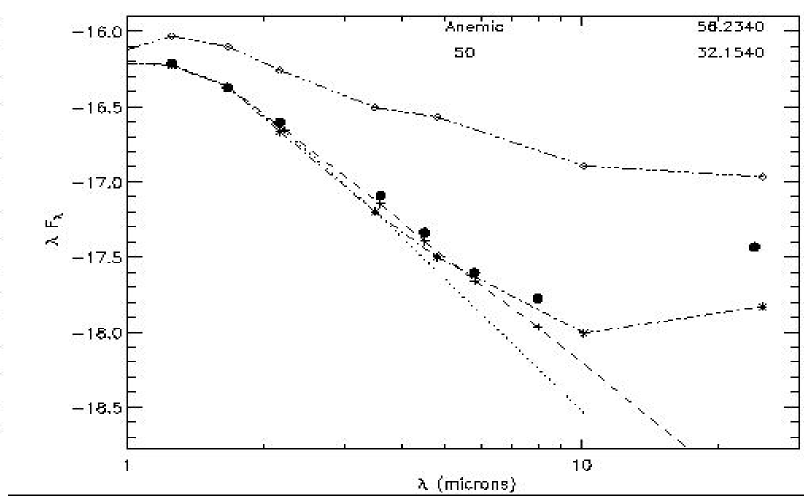
(NASA/JPL/D. Watson; D. Hines/JPL)

Accretion Signatures and SEDs of 3—5 Myr old stars are stellar mass dependent









Early-type anemic sources:
no gas accretion

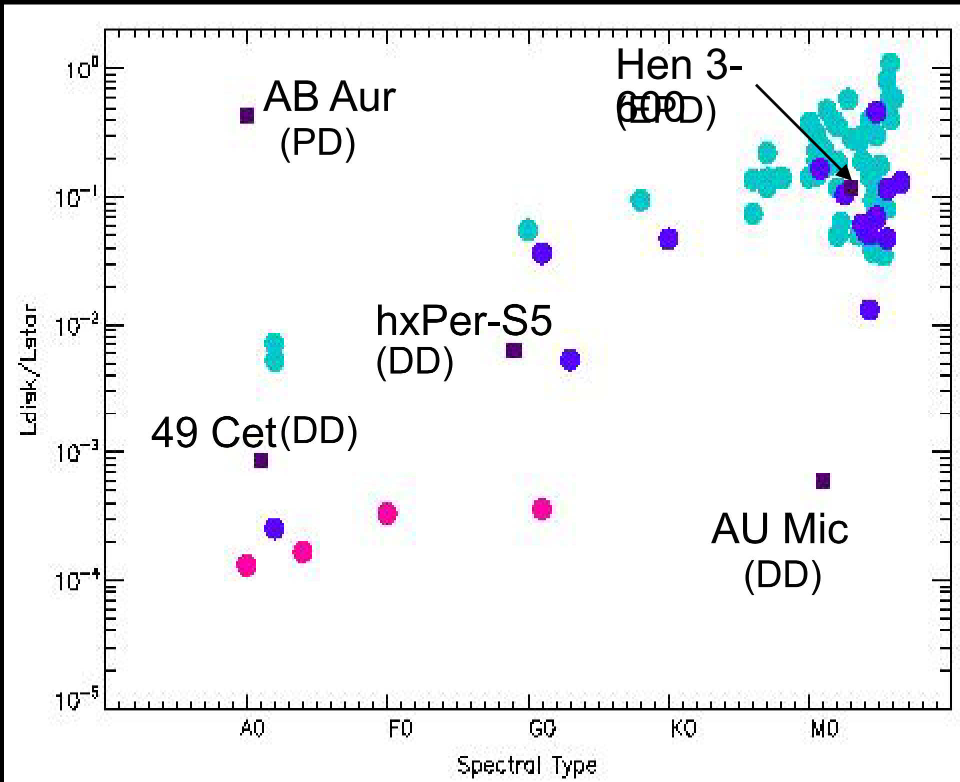
Late-type anemic sources:
many have gas accretion

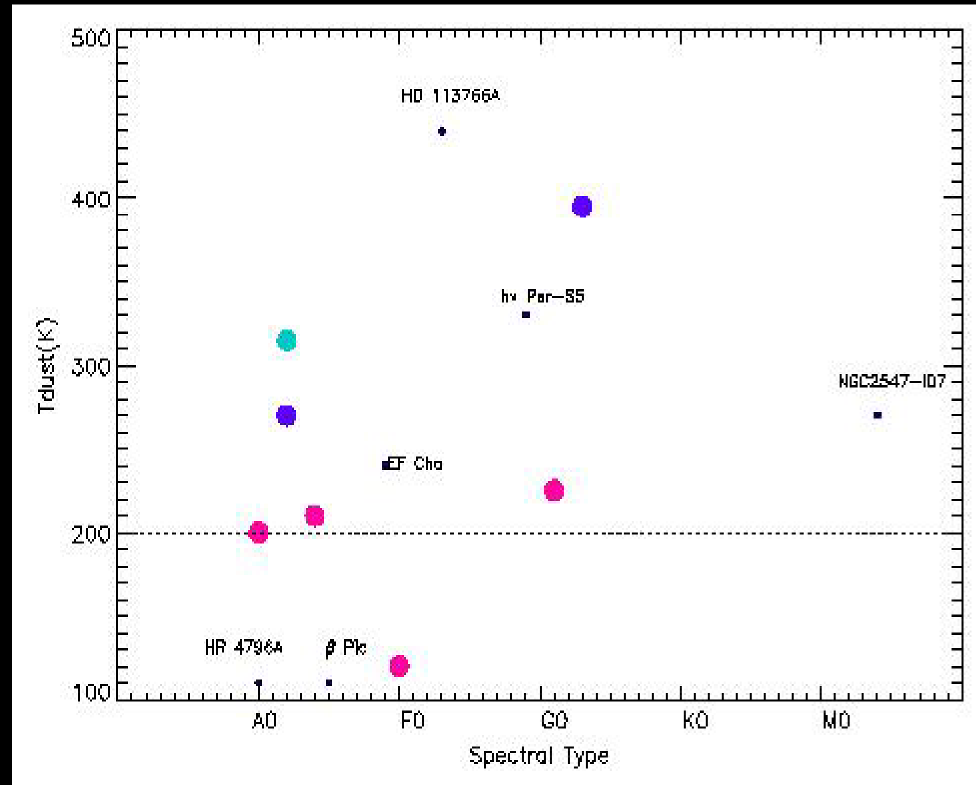
Early-type anemic sources:
terrestrial planet formation

Late-type anemic sources:
evolved primordial disks

Currie & Kenyon 2008

The Primordial to Debris Disk Transition is stellar mass dependent





Early-type anemic/diskless sources have Ld/L* typical of debris disks (10^-4 –10^-3)

Late-type sources (w/ MIPS detections) = evolved primordial disks

Intermediate types have both

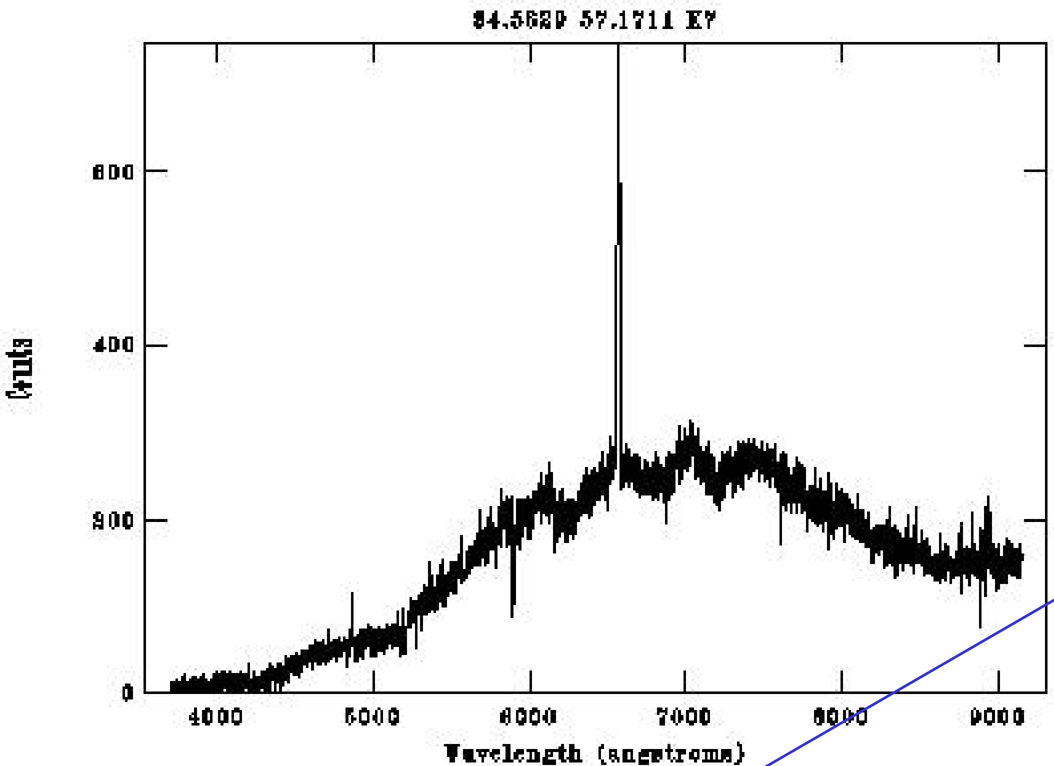
TPF can occur as soon as ~2—3 Myr

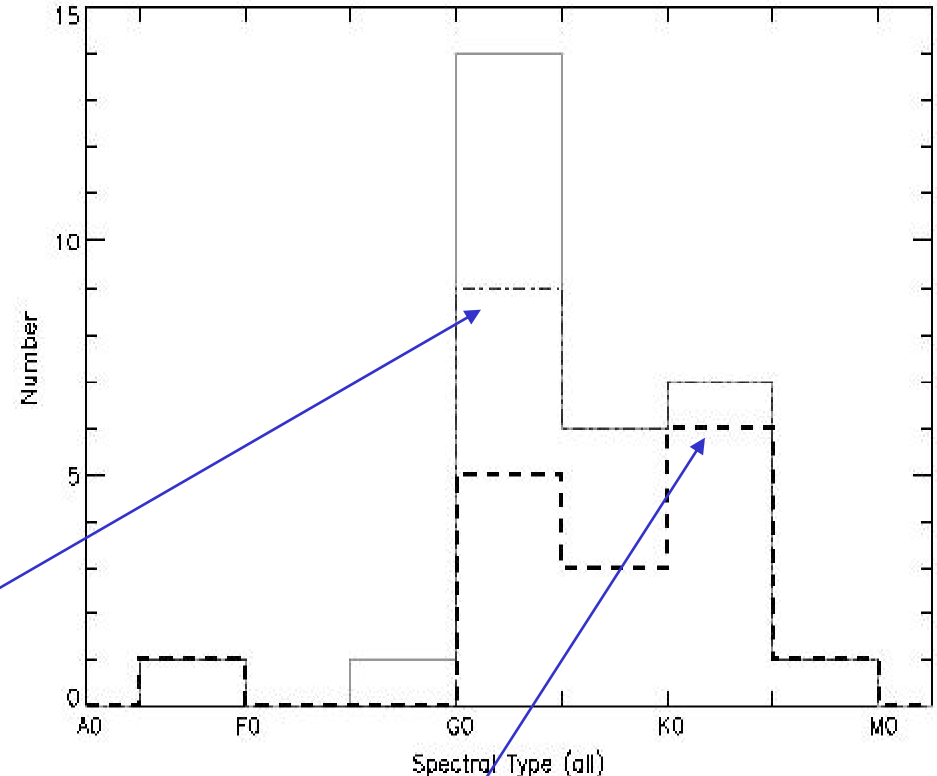
<u>High-mass (> 2 Msun) stars get to debris disk phase faster</u>

<u>High-mass stars must form gas giants by ~2--3 Myr</u>

Currie & Kenyon 2008

Gas Accretion at 13 Myr (h and χ Persei)

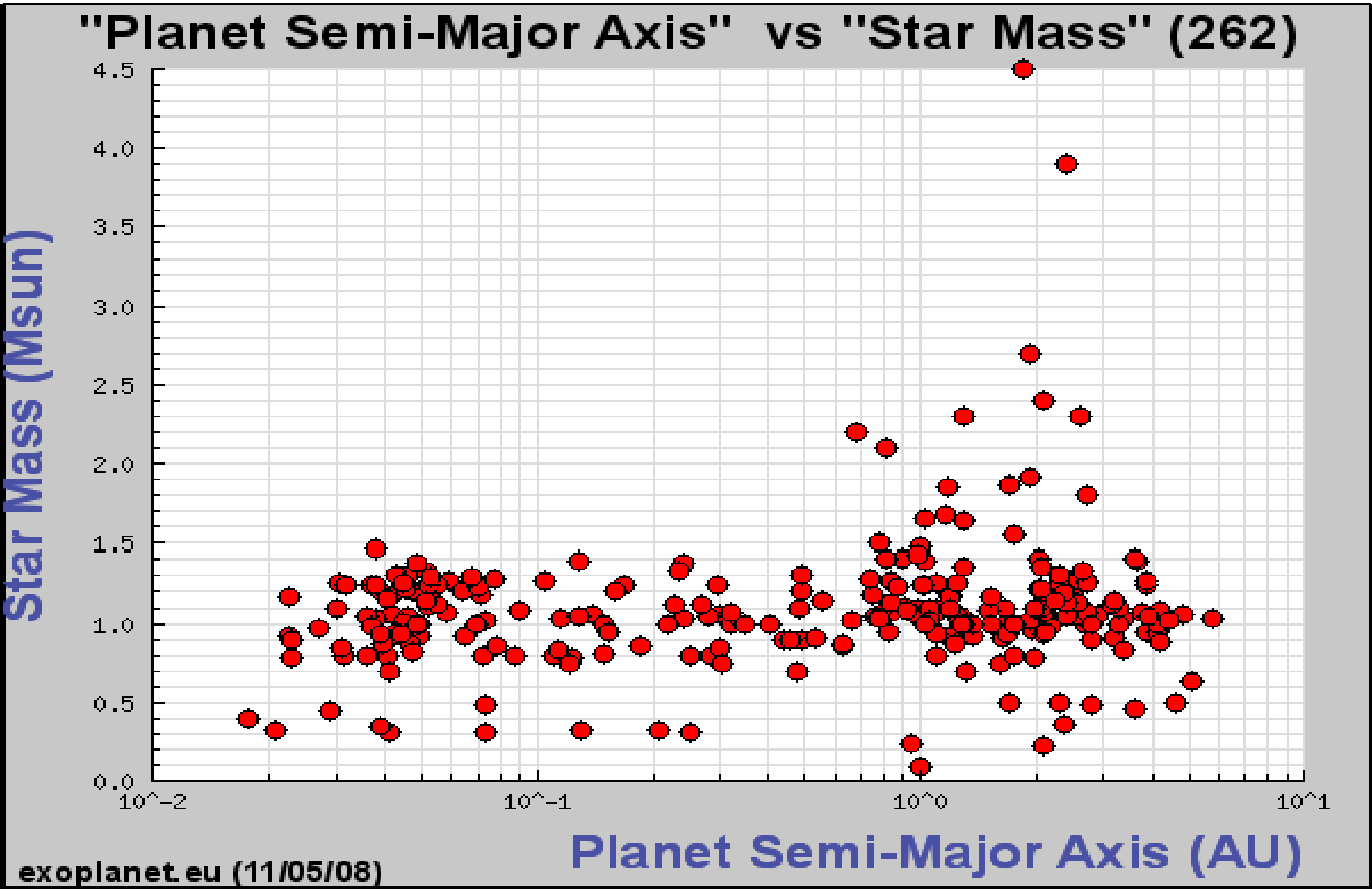




25/6,200 stars analyzed have accretion signatures (dash-dot); 16 strongly accreting (dark) (vast majority of long-lived accretors!)

Spectral-type dependence of accretors (<0.1% for < F8; ~1--2 % for > F8)?

Currie et al. 2007c, 669,



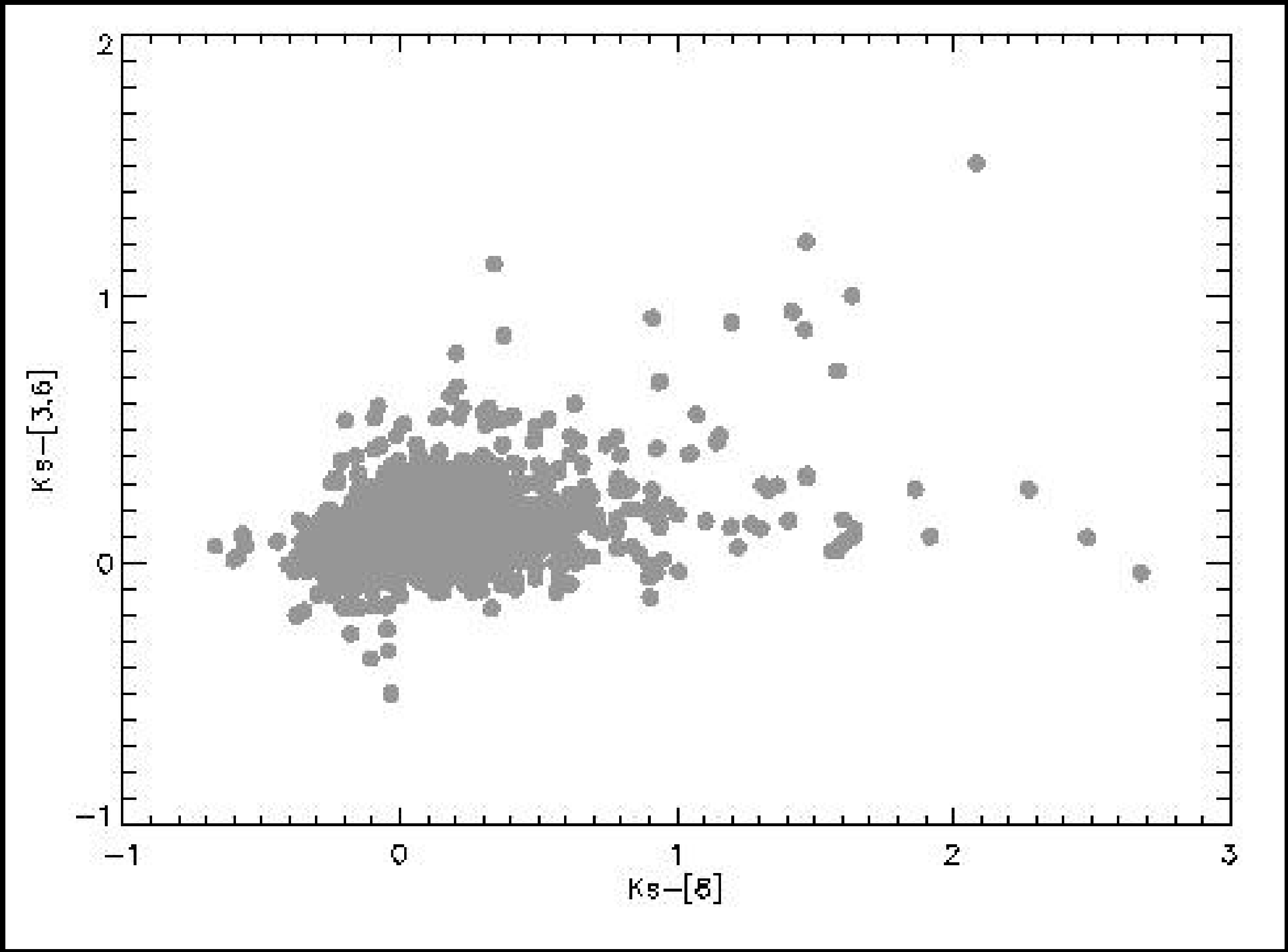
Hot Jupiters around ~0.5% of FGK stars

Lack of hot Jupiters around higher-mass stars (MS A stars)

Not a selection bias or metallicity bias (J. Johnson et al. 2007, 2008)

Could characteristics of long-lived accreting disks explain distribution of hot Jupiters??

IRAC-excess sources in h and χ Persei



Disk Modeling

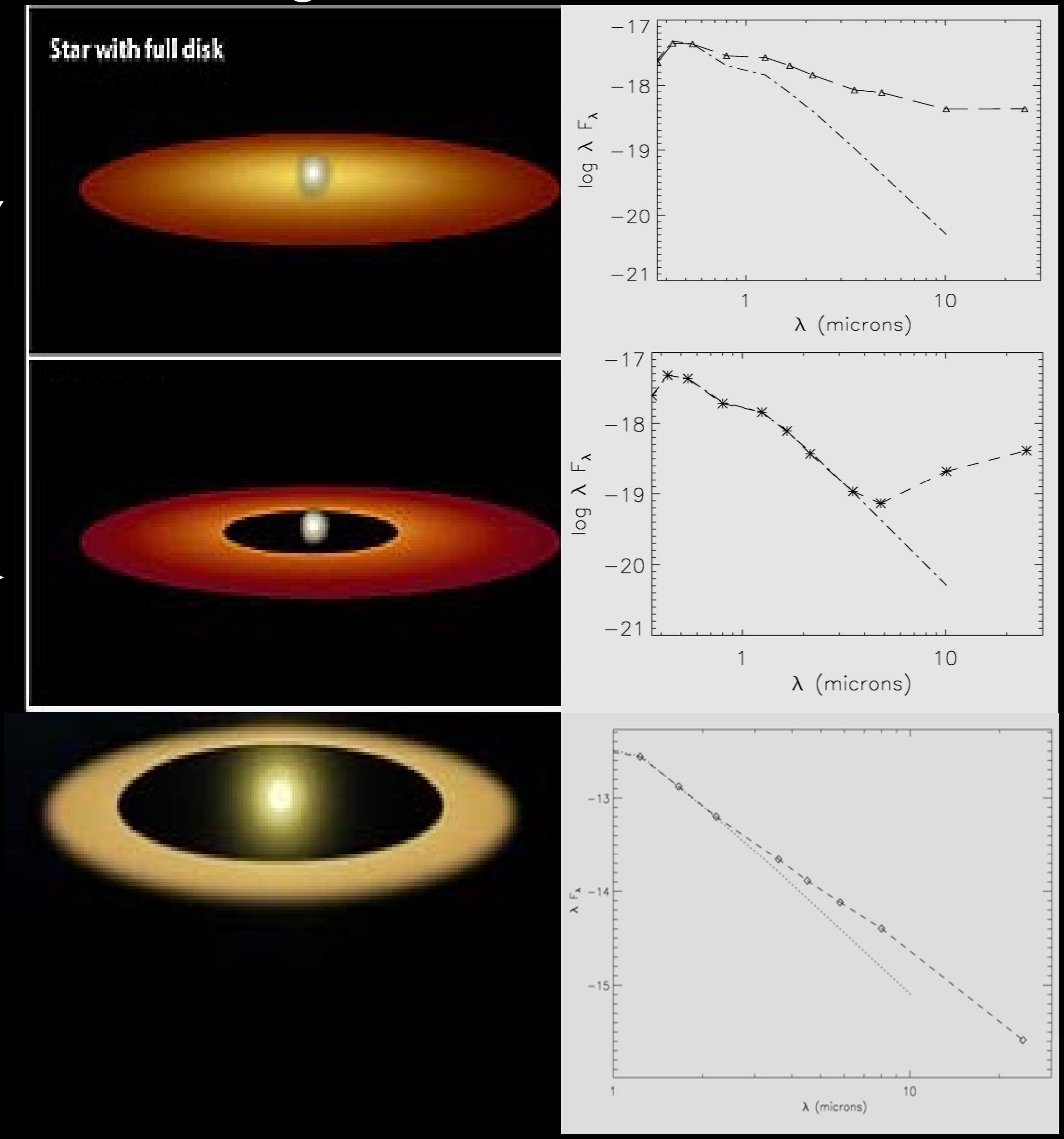
8 sources w/: Ks-[5.8] (8) > 0.5 (0.75), H'spec/FAST spectroscopy, opt. photometry

Primordial disk model (Kenyon & Hartmann 1987)

Evolved primordial disk model

Terrestrial zone debris disk model (2.0 Msun model from Kenyon & Bromley 2004)

Spectroscopy: No evidence for accretion



(NASA/JPL/D. Watson; D. Hines/JPL)

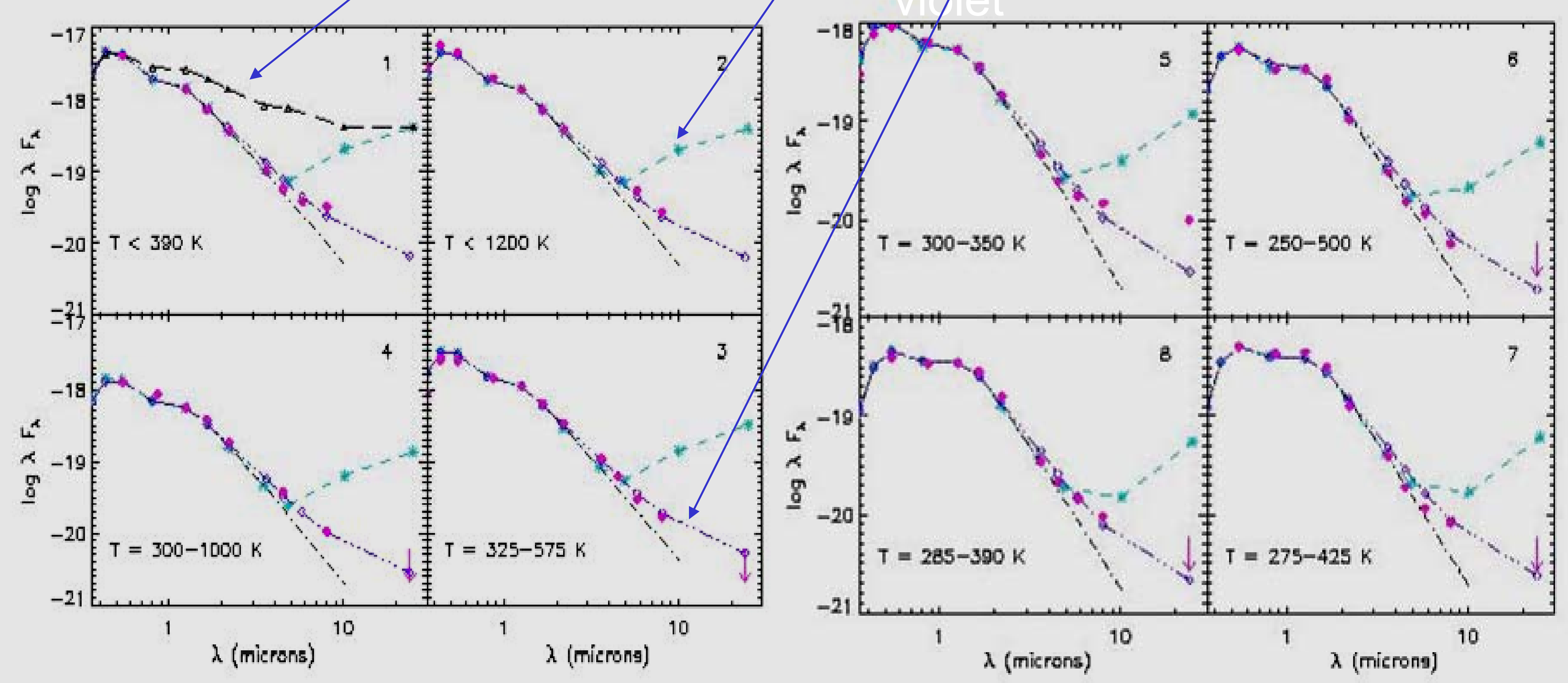
Warm debris disks in h and χ Persei: *terrestrial planet formation*

Data = magenta dots

Primordial disk model = dash/triangle

Evolved primordial disk model = cyan

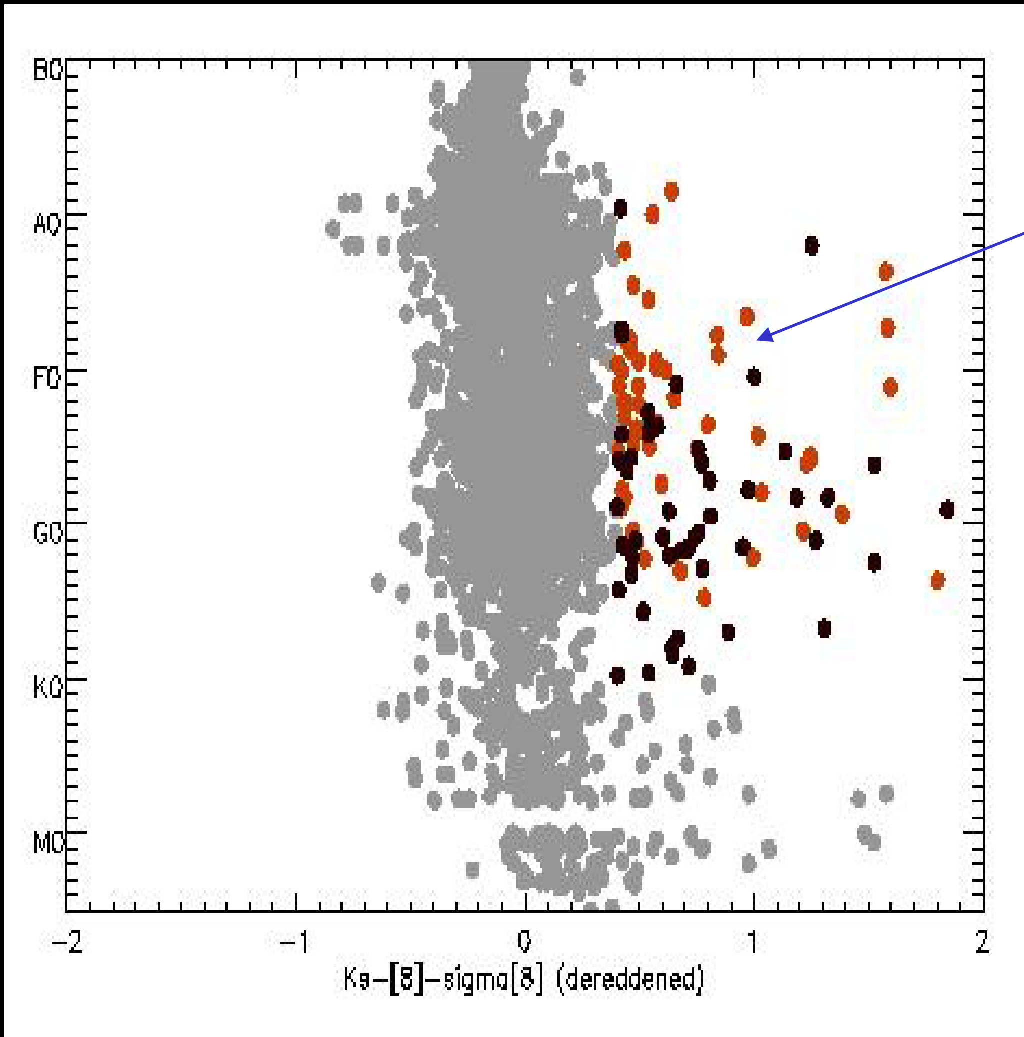
Debris disk model = violet



$L_{disk}/L^* \sim 10^{-4} – 6 \times 10^{-3}$

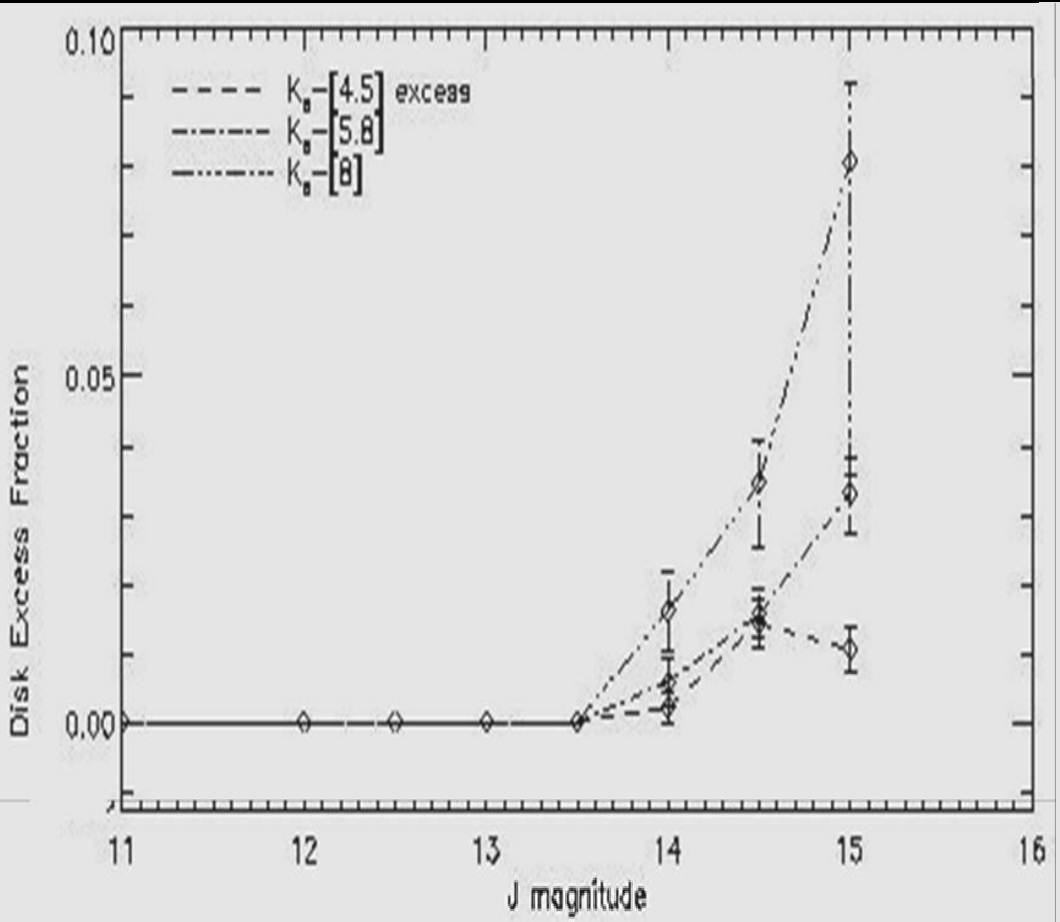
T. Currie et al., 2007b, ApJ, 663, 105L

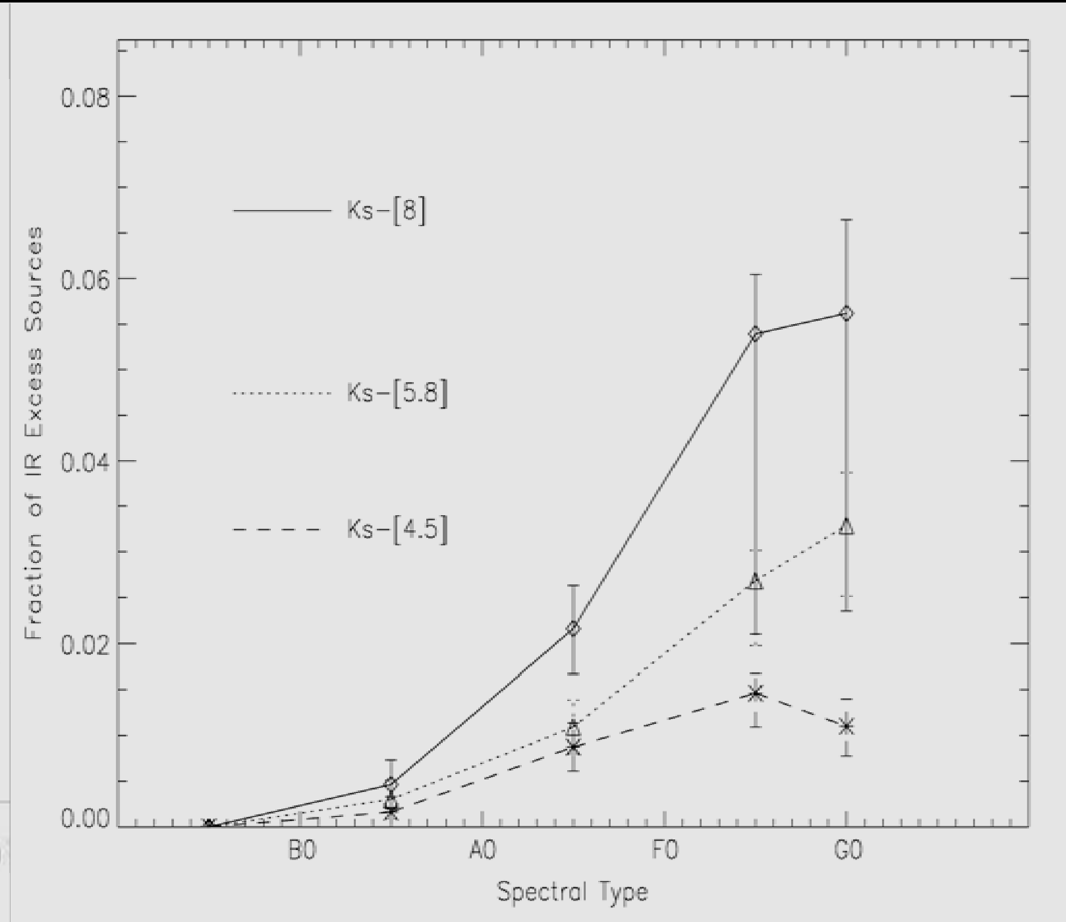
Warm, Terrestrial Zone Dust in h and χ Persei



- IRAC excess emission from warm circumstellar dust
- Quantify IR Excess Population: Criteria- Ks-[IRAC] > 0.4+σ
- Disk frequency vs. J/spectral type and wavelength

Constraints on Terrestrial Zone Disk Emission



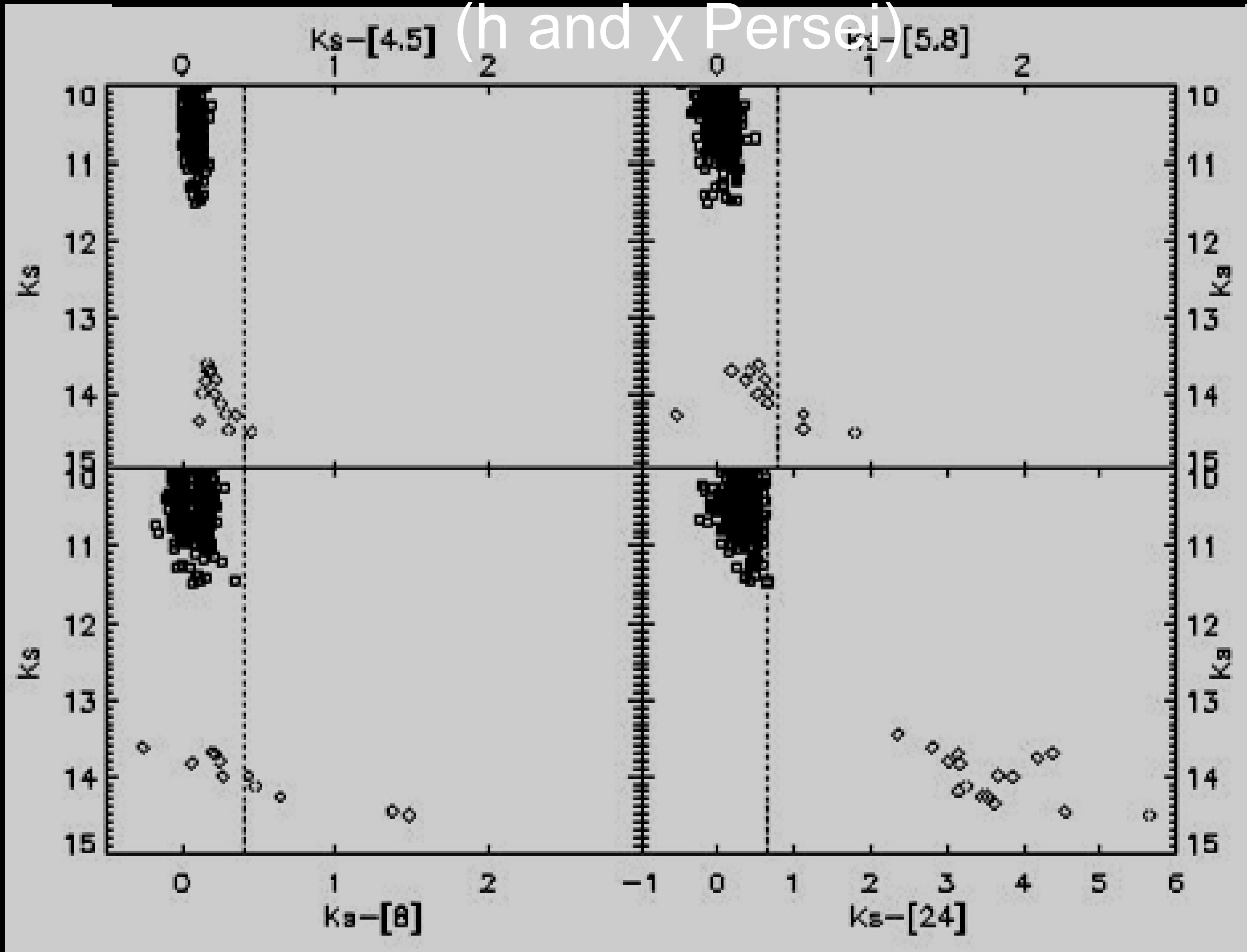


- Warm circumstellar dust emission is *spectral type/stellar mass dependent*
- Warm circumstellar dust emission is *wavelength/location-dependent*
- Debris Disks in vast majority of cases
- TPF runs to completion faster for high-mass stars than intermed. mass stars

All spectral-type bins (B0-B9; A0-A9; F0-F9; G0-G5) have > 500 stars

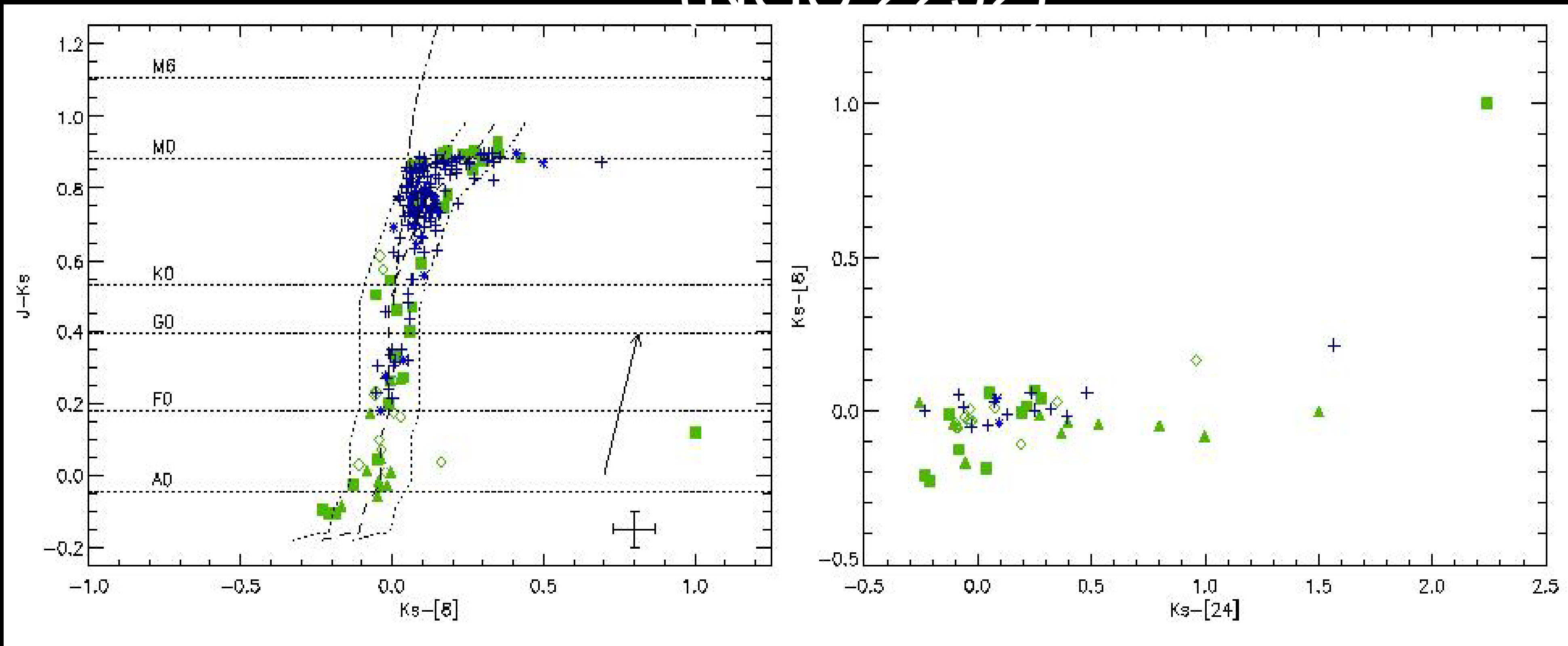
Currie et al. 2007a, ApJ, 659, 599; Currie et al. 2008

Wavelength-dependent frequency/Inside-out evolution of disks (h and χ Persei)



T. Currie, et al. 2008a, ApJ, 672, 558

Wavelength-dependent frequency/Inside-out evolution of disks (NGC 2232)



1 early type [8] excess star, 4-5 late-type (weak) [8] excess sources

8/15 early-type stars have [24] excess

one AU Mic-like star (M0, Ks-[24] ~1.5)!

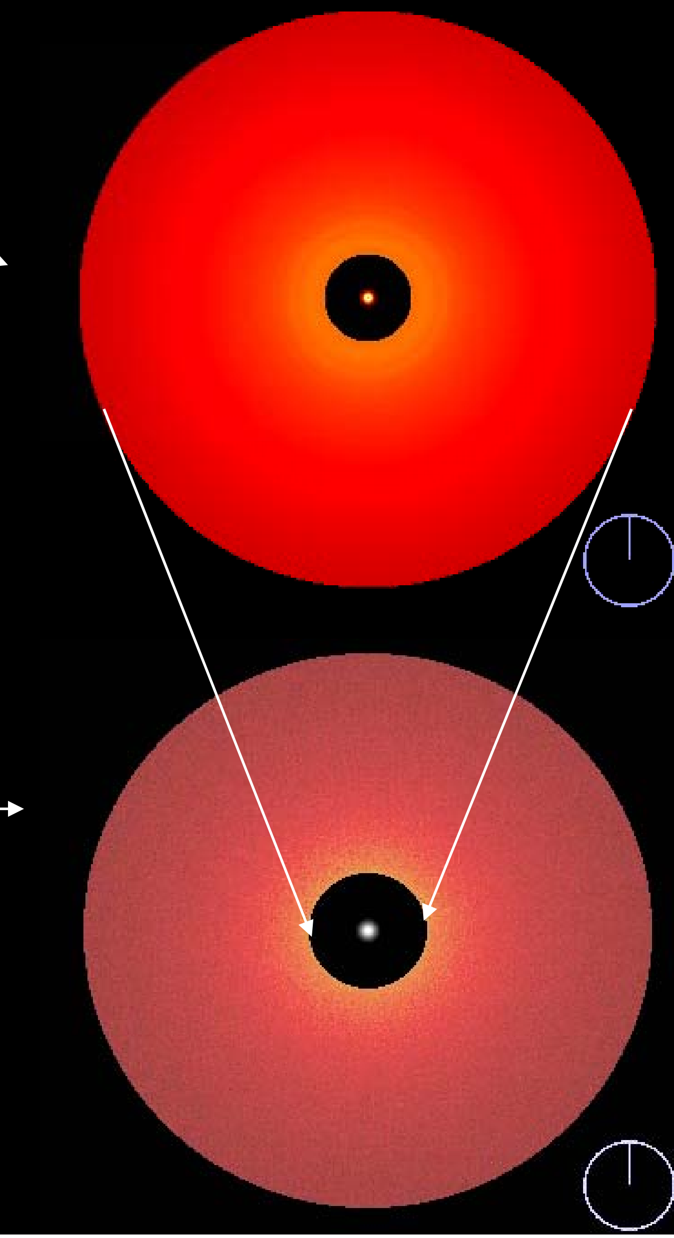
f[8] << f[24] during TPF epoch

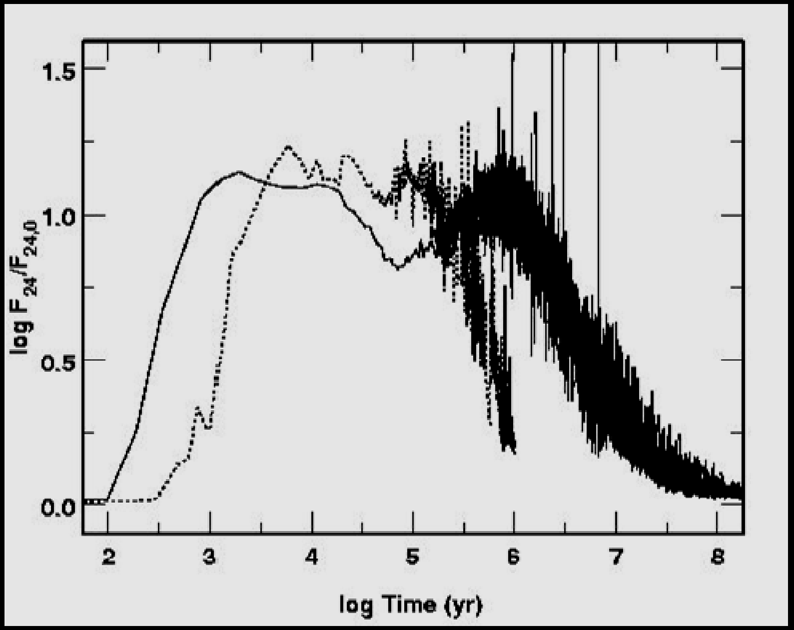
T. Currie et al., 2008b, ApJ submitted

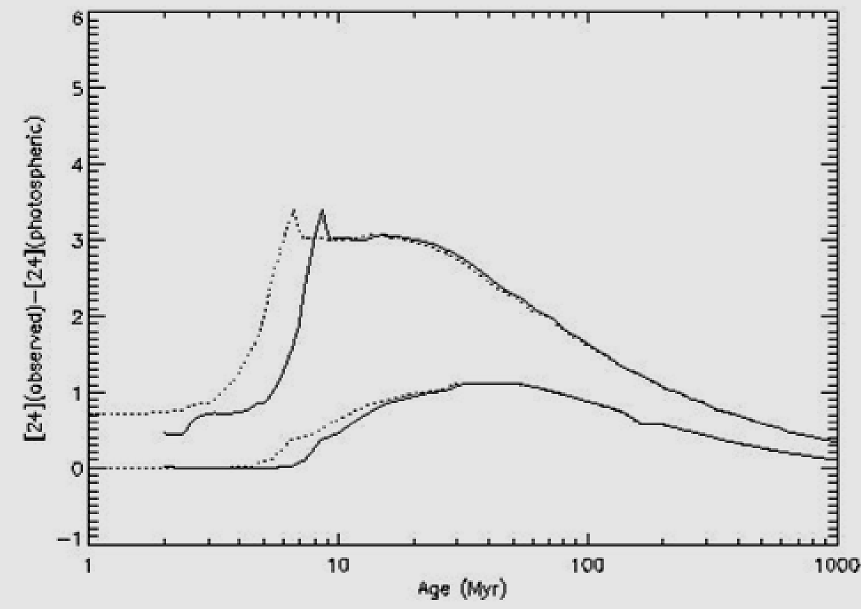
Understanding the Wavelength Dependent Disk Fraction: Inside-out Evolution of Debris Disks

Debris Disk Evolution from Kenyon & Bromley 2004

Terrestrial Zone (1.5-7.5 AU)







Ice giant/Kuiper belt (30-150 AU)

Model [24] excess sources with cold disk

Understanding the Wavelength Dependent Disk Fraction: Inside-out Evolution of Debris Disks

***Warmer* Debris Disk region**

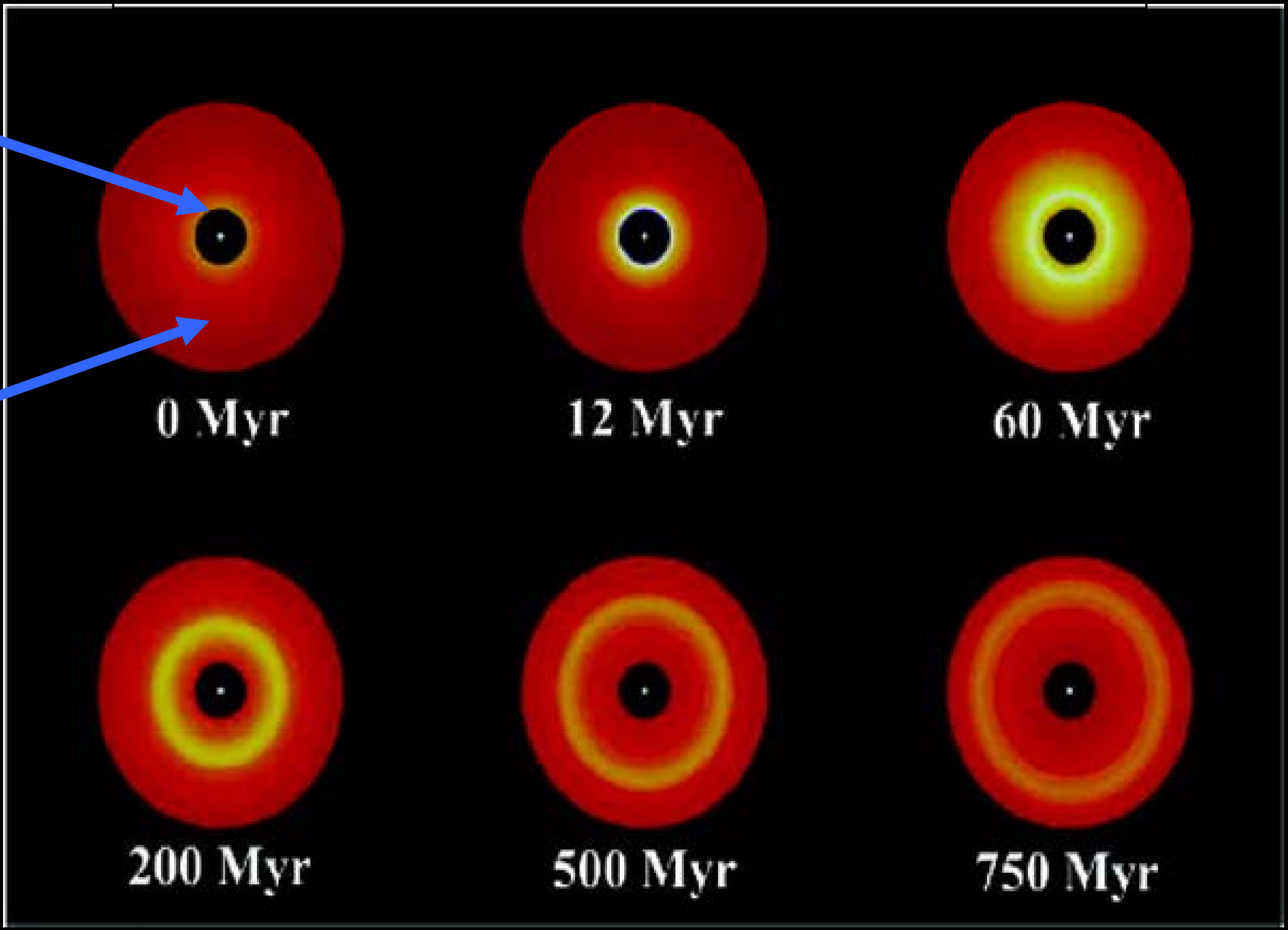
***Shorter* wavelength emission, <u>shorter</u> lifetime of emission**

***Colder* Debris Disk Region**

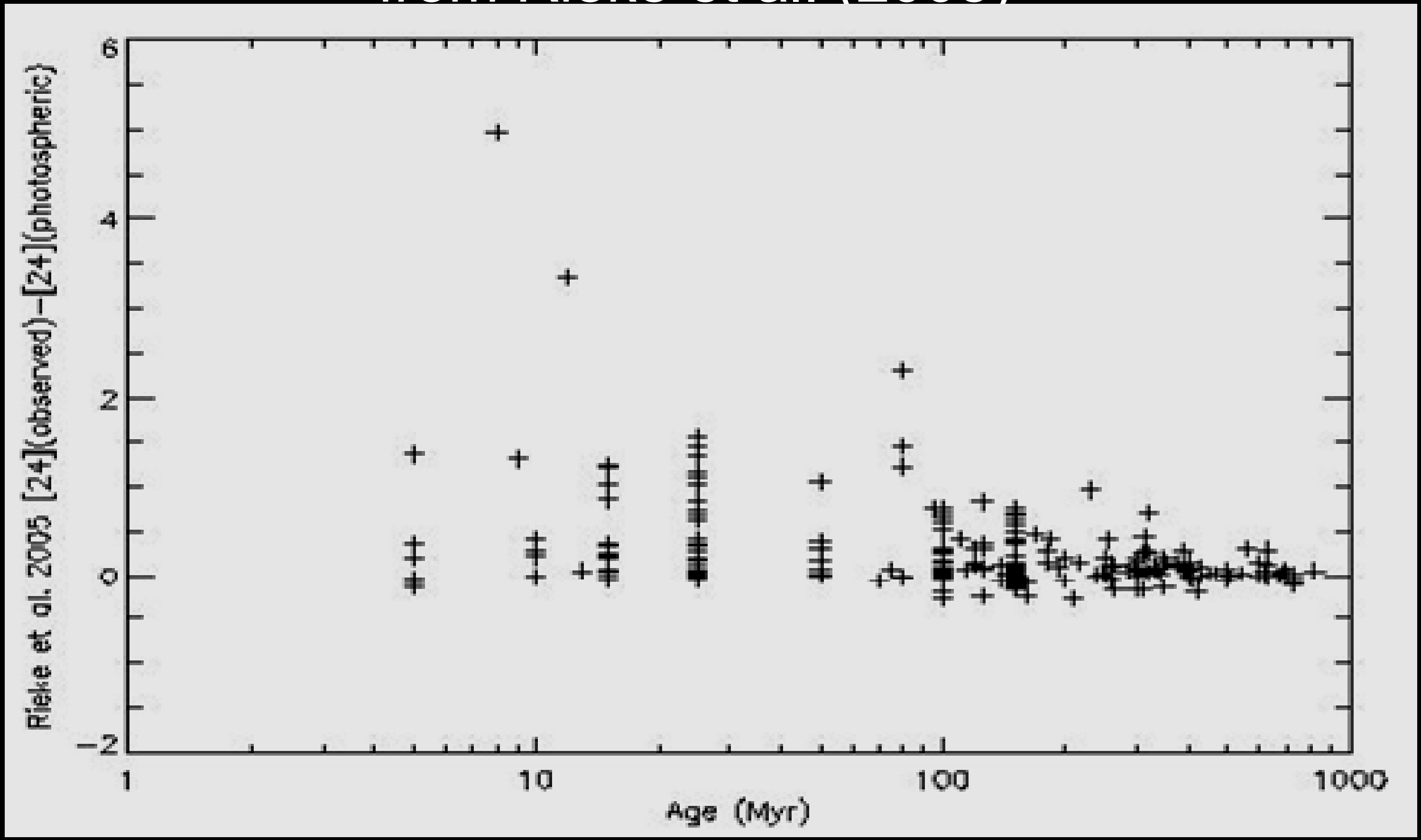
***Longer* wavelength emission, <u>longer</u> lifetime of emission**

Kenyon & Bromley 2004, 2008

Debris Disk Evolution from Kenyon & Bromley 2004



Evolution of Mid-IR Emission: power-law decay in MIPS [24] from Rieke et al. (2005)



Consistent with 1/t decline for t ~ 30 – 1000 Myr

5-30 Myr range poorly sampled

Now, add several clusters observed after:

Cepheus (4, 11.8 Myr)

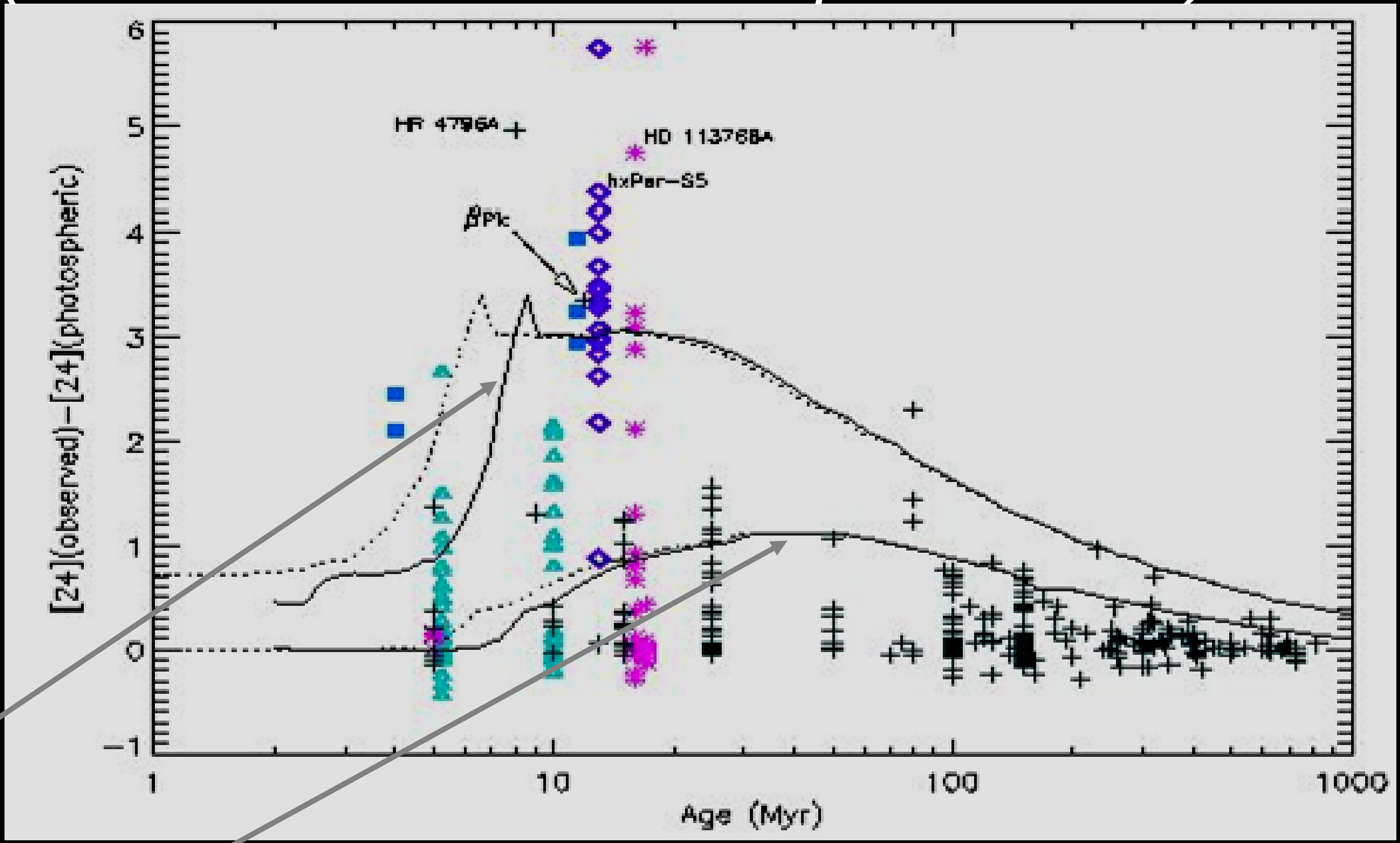
Orion OB1 (5,10 Myr)

Sco-Cen (5, 16-17 Myr)

h and χ Persei (13 Myr)

Compare with theory (high/low-mass disk)

The Evolution of Debris Emission from Planet Formation: *(from Currie et al. 2008a, ApJ, 672, 558)*



High-mass debris disk

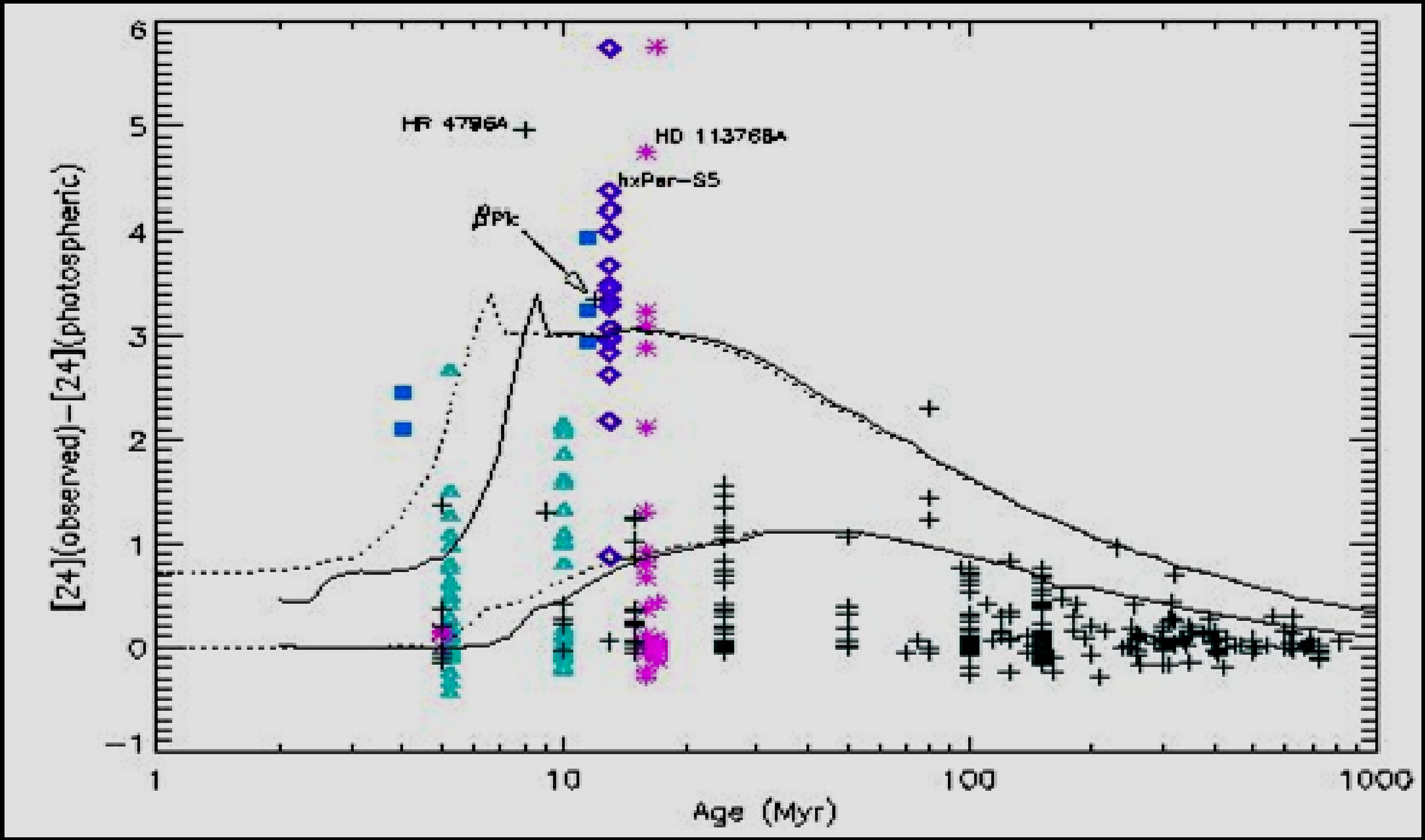
Low-mass debris disk

Cepheus --light blue
Orion OB1-- cyan

Sco-Cen -- violet
h and χ Persei -- deep purple

T. Currie et al., 2008a, ApJ, 672, 558

The Evolution of Debris Emission from Planet Formation: *The Rise and Fall of Debris Disks*



Rise in emission from 5-10 Myr

Peak in emission from ~ 10-20 Myr

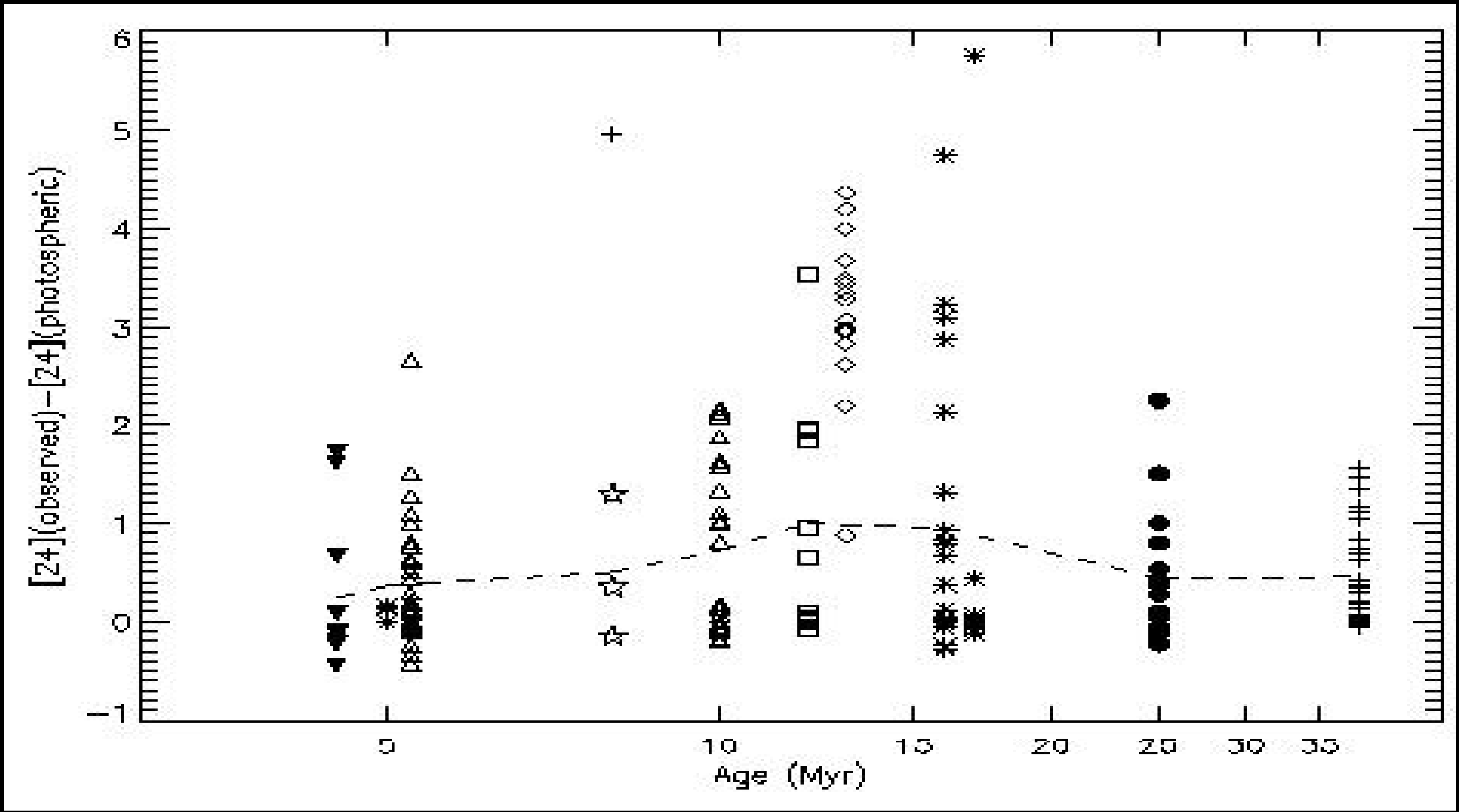
1/t decline in emission from ~ 30-1000 Myr

Trend verified by Kolmogorov-Smirnov test; Wilcoxan Rank-Sum Test

rise/peak consistent with debris disk models (Kenyon & Bromley), due to growth from ~100 km to > 1,000 km sizes

T. Currie et al., 2008a, ApJ, 672, 558

The Rise and Fall of Debris Disks (Current as of May, 5 2008)

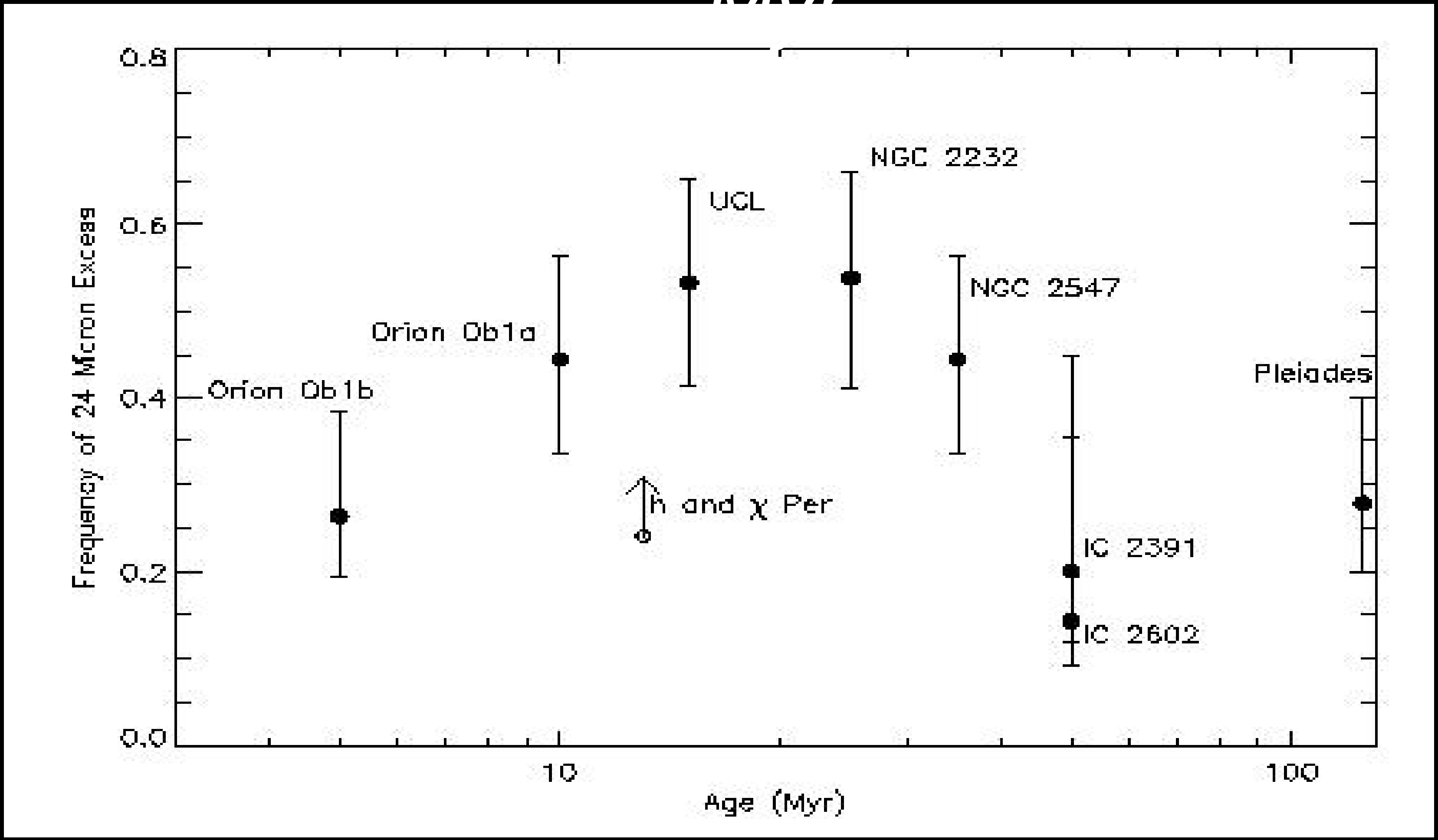


More clusters added: NGC 2362 (4-5 Myr); Eta Cha (8 Myr); BPMG (12 Myr); and NGC 2232 (25 Myr). Age for NGC 2547 adjusted to 38 Myr (Currie & Lada et al. 2008; Gautier et al. 2008; Rebull et al. 2008; Currie et al. 2008b)

Rise (5—10 Myr) and Peak (10—20 Myr) confirmed; decline from 20—30 Myr not as steep as 1/t

Peak should be later for lower-mass stars (Kenyon & Bromley 2008)

Frequency of [24] Debris Emission around B/A stars *increases* with time from 5—25 Myr



Multiple clusters have f([24] exc) > 45-50%

[24] probes dust beyond ice line

f(icy planets) > 50%

T. Currie et al., 2008b, ApJ submitted

Summary of Major Results

Timescale for gas giant planet formation is a function of stellar mass: higher-mass stars enter debris disk stage sooner (Super Earths instead of Jupiters around A stars?)

Hot Jupiters may be due to very long-lived (> 10-15 Myr) accretion disks around low-mass stars (speculative! Needs more analysis)

Terrestrial planet formation process runs faster for higher-mass stars than intermediate-mass stars

Planet formation runs fastest in inner disk regions, finishes from the inside out

Mid-IR emission from planet formation 'rises' from 5-10 Myr, peaks from 10-20 Myr, and 'falls' from ~20/30 Myr – 1 Gyr

> 50-60% of early-type (A) stars should have icy planets

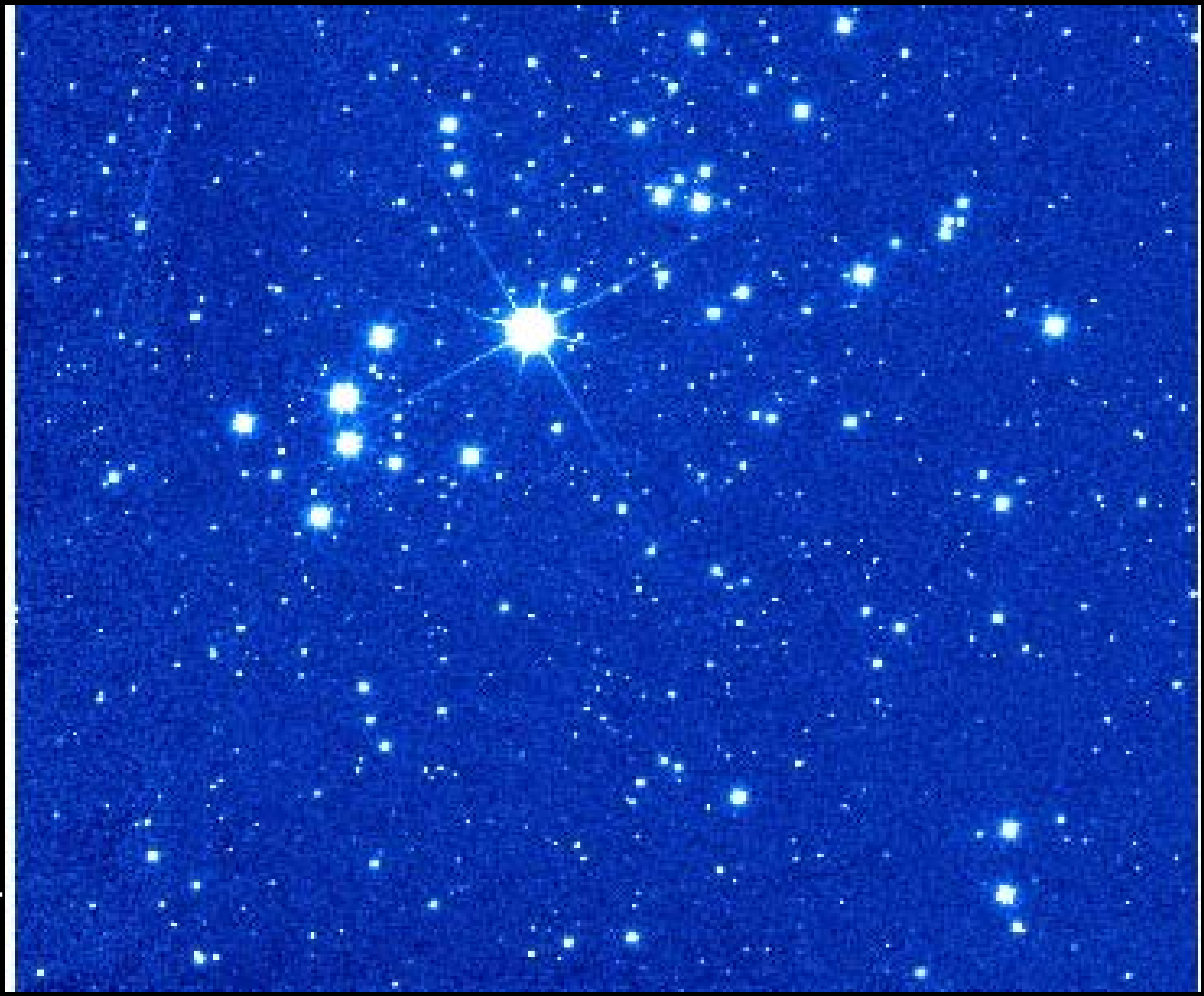
1)

105L

3) Currie et al. 2007c, ApJ, 669, 33L; 4) Currie et al. 2008a, ApJ, 672,

Future Work

- SWIRC h and χ Per J & H photometry, > *80000* stars
- Cycle 5 obs. for h and χ Per (~2 mags. deeper)
- More clusters (NGC 1960; NGC 6871, Spitzer Cycle 5)
- constraints on planet formation
- Benchmark study for JWST



(T. Currie, core of h Persei, 1.65 micron SWIRC data, unpublished)